AL-TR-1991-0171

ARMSTRONG LABORATORY

VISUAL ISSUES IN TRAINING AND SIMULATION:

PRESENTATION SUMMARIES

From the

Interagency Technical Information Exchange Meeting

1-3 October 1991
Mesa Pavilion Hilton Hotel, Mesa AZ

Hosted by: Armstrong Laboratory
Aircrew Training Research Division
Williams AFB AZ 85212

HUMAN RESOURCES DIRECTORATE
AIRCREW TRAINING RESEARCH DIVISION
Williams Air Force Base, AZ 85240-6457

December 1991

AIR FORCE SYSTEMS COMMAND
BROOKS AIR FORCE BASE, TEXAS 78235-5000

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*
December 1991

2. REPORT TYPE
Final

3. DATES COVERED *(From - To)*
1 January 2000 to October 2001

4. TITLE AND SUBTITLE
Visual Issues in Training and Simulation: Presentation Summaries

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER
62202F

6. AUTHOR(S)
Interagency Technical Information Exchange Personnel

5d. PROJECT NUMBER
1123

5e. TASK NUMBER
B1

5f. WORK UNIT NUMBER
04

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Multiple Government Organizations

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
Armstrong Laboratory
Human Resources Directorate
AircrewTraining Research Division
Williams AFB AZ 85240-6457

10. SPONSOR/MONITOR'S ACRONYM(S)
AL; AL/HR

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Approved for public release; distribution is unlimited.

13. SUPPLEMENTARY NOTES
Interagency Technical Information Exchange Meeting, held 1-3 October 1991, at the Mesa Pavilion Hilton Hotel, Mesa AZ

14. ABSTRACT
This report contains summaries of the information presented at the Interagency Technical Information Exchange meeting, hosted by Armstrong Laboratory's Aircrew Training Research Division, Williams AFB AZ, in October 1991. The subject of the meeting was visual issues in training and simulation. Paper topics included: Display image quality; Psychophysical assessment of wide-field, variable resolution imagery; Eye measurement system for flight simulation; Eye movement behavior of pilots; Vision and visibility issued in US Navy landing craft; Use of color in flight simulators; Determinants and consequences of smooth pursuit; Infrared imagery in flight; Night flights over featureless terrains; Training system definition for a Navy visual simulator; Vision research at the FAA Civil Aeromedical Institute; Vision research at NASA Ames FLM Branch; Ongoing R&D in night vision devices; Visual limitations of night vision devices; Visual system transport delay on pilot performance; Visually induced motion sickness; Vision on manual control and spatial orientation; Flight simulator side effects; Flight simulation visual research by the US Army; Cuing and scene content requirements for low level flight; Performance effects on pilot tasks; Vision research at AL/OEDL; Grating effects following laser-produced central retinal lesions; Human spatial vision; Target acquisition simulation; Target identification requirements; Aided night vision training; and Night vision device training research at Williams AFB AZ.

15. SUBJECT TERMS
Visual systems; Motion sickness; Virtual reality; Training; Mission rehearsal; Flight simulators; Flight control; Performance; Acuity; Human spatial vision; Target detection; Target acquisition; Displays; Resolution; Eye movement; Color; Smooth pursuit;

16. SECURITY CLASSIFICATION OF: a. REPORT	b. ABSTRACT	c. THIS PAGE	17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON / 19b. TELEPHONE NUMBER *(include area code)*
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	UNLIMITED	138	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

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EFFECTS OF VISUAL SYSTEM TRANSPORT DELAY ON PILOT PERFORMANCE

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Introduction

Transport delay has been a concern in many man-machine systems. It has been especially problematic in real-time systems, such as flight simulators, because of the high cost of minimizing delay and the potential impact on simulator effectiveness. This has led to a concern in the simulation community with determining how much transport delay or other temporal distortion is acceptable.

Naturally, there are several dimensions along which acceptability can be evaluated. These include: pilot ratings of simulator flying qualities, pilot performance in the simulator, and transfer of training from the simulator to the aircraft. A review of the literature conducted several years ago showed that there was a significant amount of data concerning transport delay and the performance of laboratory tracking tasks. However, few data were available on the effects of delay on transfer of training, the effects of delay as a function of aircraft type, and the effects of delay on realistic flight tasks. Because of widely differing methodologies, it was difficult to determine the relative delay sensitivity of pilot ratings, pilot performance, and transfer of training.

Therefore, the Human Engineering Division of the Armstrong Laboratory began a multi-year investigation of the problem with the sponsorship of the Aeronautical Systems Division, Training Systems Program Office. This research program will be completed with the publication of a guide entitled Time Delay and Synchrony in Flight Simulators in 1992. This paper briefly summarizes the findings of this research program as well as the results of other work addressing the simulator temporal fidelity issue.

Background

Before beginning the discussion of the research findings, it is useful to define a few terms. Transport delay, or pure time delay, is simply dead time in a system. Transport delay does not change the shape of a waveform. It simply shifts it in time, regardless of the frequency content. If the system includes dynamic elements (e.g. filters), these elements will produce phase lag or lead when the input is a periodic waveform. Because their filtering action depends on the frequency of the input, such elements will typically change the shape of a complex waveform.

There are numerous sources of these temporal distortions in flight simulators. One source is the digital computations involved in the simulator

aerodynamic model. A more important source is the image generation system typical of current flight simulators. Once the image generator has received the current aircraft state information from the aerodynamic model, the required display cannot be generated instantaneously. Some finite time period is required. Typically this is one or more time frames of the image processor, and the resulting delay will be in the range of 50-100 milliseconds (ms).

Other elements of the flight simulator that produce phase lags or pure time delays include physical data holds in the digital to analog conversion (DAC) process, low pass filters to smooth DAC outputs, data holds between subsystems operating at different iteration rates, and any delays or dynamics associated with the actual display devices (CRT frame rates, motion base dynamics, etc.).

Effects of Delay on Pilot Ratings and Performance in the Simulator

Axis of Aircraft Control

Three research studies have investigated the effects of time delay on various axes of flight control. Cooper, Harris, and Sharkey (1975) measured the performance of pilots flying simulated carrier approaches with and without an additional 100 ms delay inserted in the CIG display loop. The authors do not give the baseline delay value. The only effects observed on pilot behavior were in lateral-axis control. Ricard, Norman, and Collyer (1976) assessed the performance of simulated straight-and-level flight in the presence of mild turbulence. An artificial horizon display was provided and delays of 17.5 to 1400 ms were investigated. While control of pitch angle was hardly affected by the delays, roll errors tended to increase when the delay exceeded 100 ms. In more recent work at the Armstrong Laboratory, Riccio, Cress and Johnson (1987) found that lateral-axis control was more sensitive to added delay than altitude control. In this experiment, subjects were attempting to maintain a specified heading and altitude in the presence of strong turbulence (Figure 1).

Aircraft Dynamics

Queijo and Riley (1975) investigated pure time delays of 47-297 ms using the NASA Visual Motion Simulator (VMS). The simulator was used in a fixed-base mode, and pilots tracked a vertically oscillating target driven by a 0.03 Hz sinusoid. This represented a relatively easy tracking task. Seventeen configurations of aircraft dynamics were investigated, covering a range of excellent to poor handling qualities. All configurations included a baseline transport delay of 47 ms. Delays of 0-250 ms were added to this baseline. The authors found that tolerable delay is not a monotonic function of aircraft responsiveness (Figure 2). That is, both sluggish and highly responsive aircraft appeared to be less tolerant of delays. Unfortunately, the analyses did not permit one to determine if the differences were statistically significant.

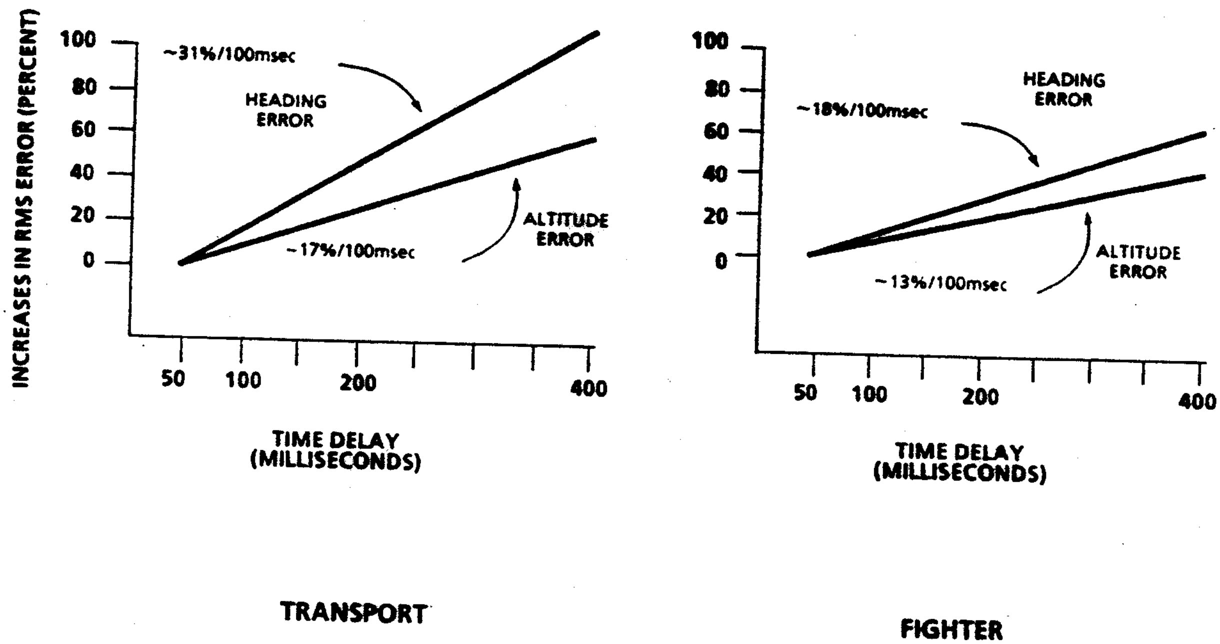

FIGURE 1. EFFECTS OF TIME DELAY ON HEADING AND ALTITUDE CONTROL PERFORMANCE WITH SIMULATED FIGHTER AND TRANSPORT DYNAMICS. (From Riccio, Cress and Johnson, 1987)

Recent experiments, which have used more demanding flight control tasks than Queijo and Riley (1975), provide some assistance in interpreting the above results. Studies at the Armstrong Laboratory (Riccio, Cress and Johnson, 1987) evaluated the effects of time delays on performance with simulated fighter and transport dynamics. Both simulated aircraft included baseline transport delays of 50 ms. Delays of 0-350 ms were added to this baseline. The flight task required the subjects to maintain a constant heading and 100 ft. altitude over flat terrain. Wide-bandwidth turbulence continually perturbed the aircraft's flight path. This task, although idealized, was quite demanding. The percent change in root-mean-square error with time delay is shown in Figure 1. Although the delay effects were somewhat larger for the transport aircraft, the differences between the fighter and transport were not statistically significant. In both cases, delay significantly degraded heading and altitude control.

As part of the Armstrong Laboratory research program, Calspan Corp. completed a series of studies using the NT-33 variable stability aircraft in both its ground-based and in-flight modes. The data from some of this work (Bailey et al., 1987) are summarized in Figure 3. Four aircraft configurations were chosen to cover a range of aircraft sizes and missions. It should be noted that these studies utilized only low-order approximations to the aircraft dynamics and control feel systems. None of the configurations were high fidelity simulations of the actual vehicle. The pilots flew a variety of demanding tasks selected to permit sensitive flying

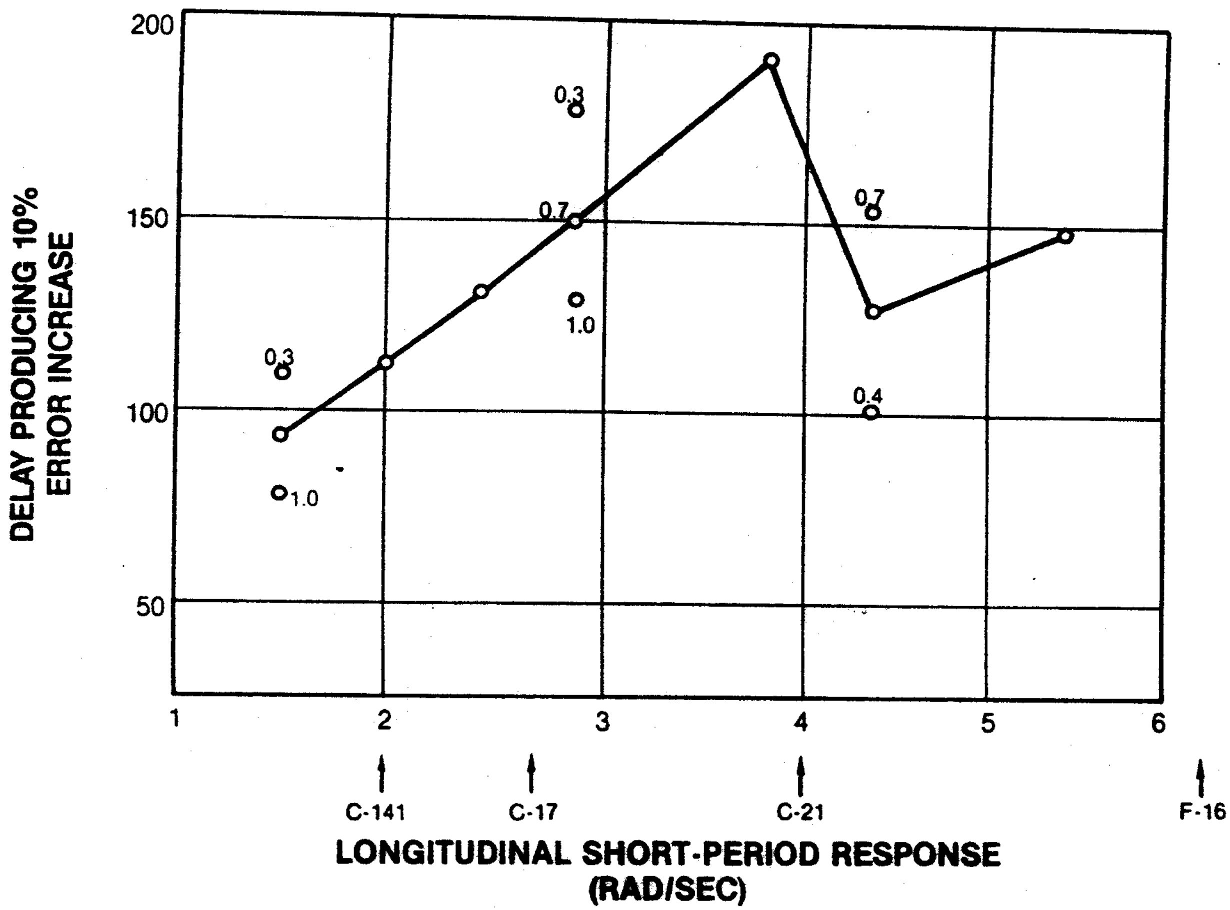

FIGURE 2. TOTAL TRANSPORT DELAY REQUIRED TO PRODUCE A TEN PERCENT INCREASE IN TRACKING ERROR AS A FUNCTION OF SIMULATED AIRCRAFT LONGITUDINAL DYNAMICS. The responsiveness of several aircraft are noted below. The solid line represents results averaged over several damping ratios, where appropriate. The open circles represent individual data points for the damping ratios shown. (From Ricard and Puig, 1977, who replotted Queijo and Riley's data)

quality evaluations. All tasks were presented on a head-up-display (HUD) and the pilots wore a special visor that prevented them from seeing outside the cockpit. The ground-based evaluation utilized the actual NT-33 connected to a computer system. The primary difference between the in-flight and ground-based cases was the presence or absence of aircraft motion. Each of the four simulated aircraft included a baseline delay of 100 ms over and above the aircraft phase lag. The delays shown in the figure were added to this basic delay.

The in-flight data in Figure 3 are the easiest to interpret. For all simulated aircraft, the pilots rated the baseline case (100 ms delay) as having Level 1 handling qualities. Level 1 ratings, i.e. Cooper-Harper ratings of 1, 2 or 3, are required before a new aircraft can be accepted into the military inventory. For all aircraft, the regressions fitted to the pilot ratings cross the Level 1 to Level 2 boundary at 150-200 ms total delay (50-100 ms added delay). The authors conclude that, for the tasks selected, the four aircraft were about equally sensitive to time delay. As will be corroborated in the next section, the lack of motion cues in the ground-based cases made the pilots more sensitive to delay. In fact, even the baseline delay condition was rated as Level 2 for all aircraft.

It is clear that aircraft dynamics and handling qualities are important variables when considering the effects of time delay. Nevertheless, the recent studies suggest that under <u>high task loading</u>, pilot performance and subjective ratings will be equally degraded by time delay for all types of aircraft. This conclusion is actually fairly consistent with the earlier results shown in Figure 2. In that figure, the C-141, C-17, and C-21 only show about 50 ms difference in their delay sensitivity.

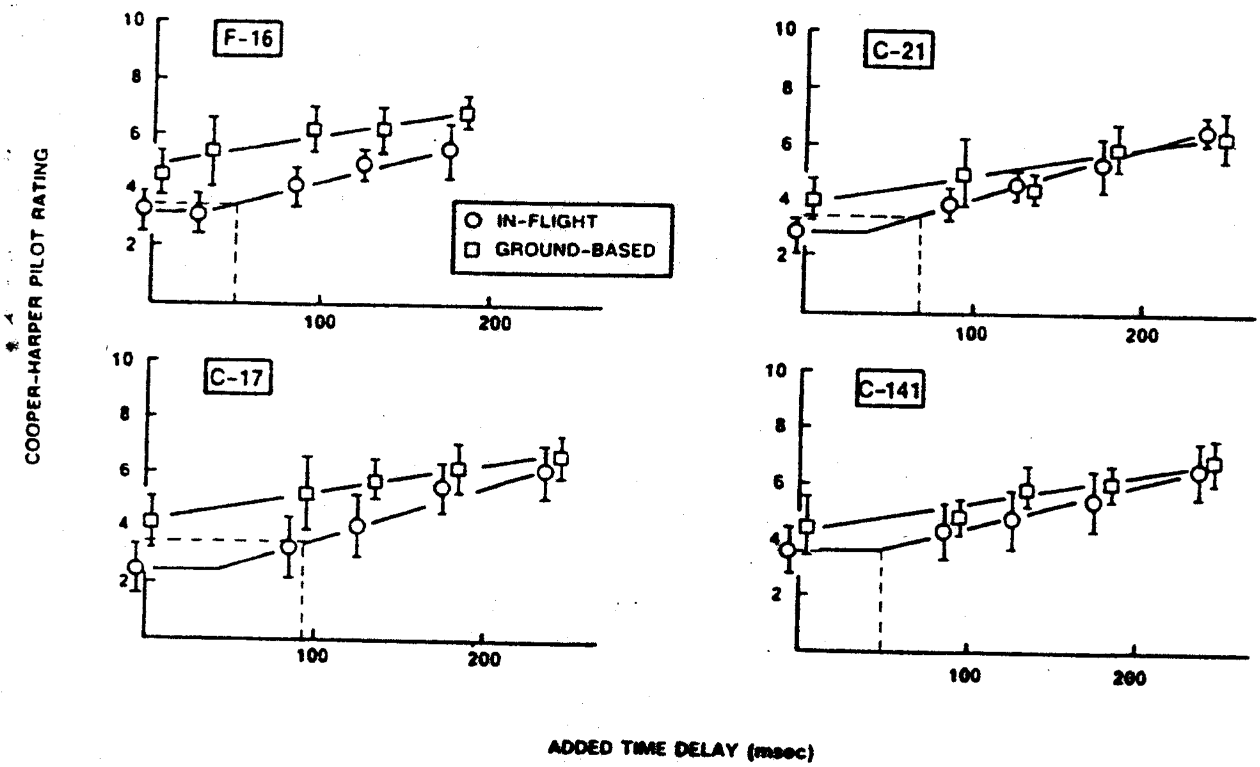

FIGURE 3. EFFECTS OF IN-FLIGHT AND GROUND-BASED SIMULATOR DELAYS ON RATED HANDLING QUALITIES FOR FOUR DIFFERENT SIMULATED AIRCRAFT. Delays shown were added to the basic system delay of 100 ms. Dotted lines show the point at which handling qualities ratings cross from Level 1 to Level 2 for the in-flight case. (From Bailey et al., 1987)

Motion Effects

By essentially repeating the Queijo and Riley study with the VMS motion base active, Miller and Riley (1976) demonstrated that providing motion cues can significantly reduce the effects of time delays. Both the visual and motion cues were delayed equally. For their "basic" airplane, which had a handling qualities rating of 5, the acceptable delay in a fixed-base mode was 172 ms. Statistically significant degradations in performance were observed for longer delays. When the motion base was active, the acceptable delay increased to 297 ms. Since motion cues are known to allow a pilot to generate additional lead compensation (Shirachi and Shirley, 1977), this result is quite reasonable. In my opinion, the absolute values of acceptable delay reported in the two VMS studies should be used with caution because of the relative ease of the tracking task, the small number of subjects, and the variation in criteria used to determine acceptable delays. However, there is no reason to believe that the trends observed in these two studies are not correct, especially given the results of the Calspan NT-33 studies reported above.

Task Type

One reason for the caveat on the two VMS studies is that task difficulty has been shown to be an important determinant of delay effects. In fact, Queijo and Riley (1975) and Miller and Riley (1976) also manipulated the difficulty of their tracking task. When the target frequency was doubled, the acceptable time delay decreased by a factor of two to three. Sevier, et al. (1984) investigated the effects of 110 vs. 160 ms visual system delays on the performance of two tasks: (1) tracking a target which was oscillating vertically, or (2) maintaining a constant 45 degree bank angle using a constant-rate turning target as a reference. Effects were only observed for the more difficult pitch tracking task.

In our research program, a number of flight control tasks have been investigated. In the most recent work, delay effects on a sidestep landing maneuver (Whiteley and Lusk, 1990) and on a low-level flight task (Middendorf, Fiorita, and McMillan, 1991) were evaluated. In both studies the baseline fighter aircraft dynamics included a transport delay of 90 ms, similar to the Calspan study reported above. This baseline delay is actually representative of modern fighter aircraft such as the F-16. Delays of 110 or 210 ms were added to this baseline case. For both tasks, total delays of 300 ms produced statistically significant degradations in performance and were clearly unacceptable. Total delays of 200 ms degraded some aspects of performance in both experiments, and probably represent the maximum permissible delay for these tasks. Figure 4 presents some representative data from the low-level flight experiment.

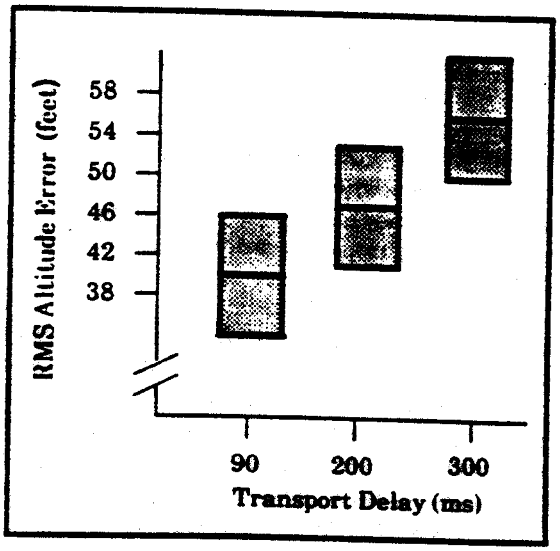

FIGURE 4. EFFECTS OF TRANSPORT DELAY ON ALTITUDE ERROR IN A SIMULATED LOW-LEVEL FLIGHT TASK. Subjects were required to fly at an altitude of 175 feet over rolling terrain. Bars show the mean plus and minus the 95% confidence intervals from a Tukey's multiple-comparison test. (From Middendorf, Fiorita, and McMillan, 1991)

Effects of Delay on Transfer of Training

Because so few data were available in the literature, several experiments in the Armstrong Laboratory program have investigated the effects of delay on transfer of training. The Riccio, Cress, and Johnson study (1987) cited above is one example. An interesting pattern has emerged from this work. First, delays of 100 ms or less seem to have a slight (but nonsignificant) positive effect on transfer. Perhaps the delay compensation skills learned during training permit the subject to apply even higher bandwidth control when the delay is removed. Second, significant transfer degradation does not occur unless training delays are in the 300-400 ms range. These and other data strongly suggest that delays have a greater negative effect on performance than on the transfer of training.

Guidelines for Acceptable Transport Delay

Despite the relatively large data base concerning the effects of transport delay errors on pilot performance, clear standards exist only for commercial aircraft simulators. At least two problems contribute to this situation. First, most of the systematic research has used inconsistent criteria to determine "acceptable delays", has used very few subjects, and has employed idealized tasks which are difficult to generalize to a complex full-mission simulator. Second, the state-of-the-art in computer power

still makes it difficult to achieve even the tentative standards the research suggests. Naturally, we are reluctant to set standards that cannot be realized at an acceptable cost. If there is a consensus among experts, it appears that a value of 100 ms is most likely to be quoted as a maximum acceptable delay for high performance aircraft (USAF Scientific Advisory Board, 1978; Ricard and Puig, 1977). Although not explicitly stated, one may assume that this delay may be added to the response time of the simulated aircraft.

With the advent of digital fly-by-wire aircraft and complex flight control computers, the effects of higher order dynamic modes and inherent time delays have been of great concern to the aircraft design community. Based upon research addressing this issue, 100 ms has been established in the military specification for piloted-vehicle handling qualities (MIL-F-8785C) as the total equivalent and/or pure time delay that can be included between control input and aircraft response. This requirement is independent of aircraft size and mission. This specification does not address the issue of how much additional delay can be added in a flight simulator before performance, training, or pilot acceptance is degraded. It does point out, however, that a faithful aerodynamic model for current military aircraft may include a significant amount of delay before simulation artifacts are added. To the pilot, the source of delay is largely irrelevant. He only experiences the effect of the total amount of delay.

The one published standard for cue synchronization applies only to commercial airline simulators. In Advisory Circular AC 120-40A (FAA, 1986) simulator response standards are specified for Phase I, II, and III simulators. For Phase I simulators, which only permit certification of certain landing tasks, the FAA specifies that the visual system response time to pilot control input shall not be more than 300 ms longer than the actual aircraft response. For Phase II systems, which permit transition and upgrade certification, 150 ms is the maximum added time delay for any of the display systems. In addition, the rule specifies that the visual scene changes shall not occur before the acceleration response of the motion base. The same synchronization standard applies to Phase III simulators, which permit all but the line check, the static airplane requirements, and the flight experience requirements to be performed in the simulator. The reader should note that if the aircraft being simulated has equivalent or pure time delays that meet the above military specification, the total delay in a Phase III simulator could be 250 ms.

As a means of providing consistent data for military simulations, the Armstrong Laboratory is preparing a guide entitled <u>Time Delay and Synchrony in Flight Simulators</u> which will be published in 1992. This handbook will focus on the data collected in our laboratory and at Calspan Corp., because of the consistent experimental design and analysis procedures used in this large research effort. Rather than providing specific "acceptable delay" numbers, the handbook will provide functional relationships between time delay and (1) performance, (2) transfer of training, and (3) handling qualities ratings, for different flight tasks and aircraft dynamics. Thus

the user can determine what level of performance or training degradation he is willing to accept in return for time delay.

Although we believe that this is a more useful approach than providing specific delay criteria, users do need rules of thumb to guide their thinking. Based upon the currently available data and subject to change, I would suggest the following rules of thumb:

(1) To ensure Level 1 handling qualities in the simulator, the sum of aeromodel equivalent delays, aeromodel pure time delays, and added simulator delays should not exceed 150 ms. This value is up to 100 ms more stringent than the FAA Phase II/III value since it considers the delays included in the aeromodel.

(2) To minimize delay effects on pilot performance in the simulator, the sum of aeromodel delays and simulator delays should not exceed 200 ms. For an aircraft which just meets MIL-F-8785C, this value is equivalent to the expert consensus mentioned above.

(3) To promote good transfer of training, the sum of aeromodel delays and simulator delays should not exceed 300 ms.

(4) At this time no delay guideline can be proposed with respect to simulator sickness issues.

(5) The same guidelines apply to transport and fighter aircraft, since military transport pilots often have high task demands.

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Visually-Induced Motion Sickness in Virtual Reality Systems: Implications for Training and Mission Rehearsal

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INTRODUCTION

The problem of motion sickness is an old one for the armed forces. In its "classic" form, motion sickness has been studied primarily with regard to air and sea sickness. However, as the ability to provide high fidelity simulations of self-motion has become more common, a unique form of motion sickness has arisen: Visually-induced motion sickness (VIMS). This syndrome is of concern because of the negative impact it may have for training vehicular control skills with simulation, and for the incorporation of Virtual Reality (VR) technology into operational and training systems.

VIMS appears to occur most often in situations in which observers view optical flow patterns that produce strong illusions of self-motion in the absence of actual physical displacement. Occurrences of VIMS in the military have been discussed primarily with regard to motion sickness in flight simulators (Kennedy, Hettinger, & Lilienthal, 1990; McCauley, 1984). In these situations, pilots training in fixed-base simulators may develop signs and symptoms normally associated with classic motion sickness (e.g., nausea, pallor, sweating) and others which appear to be unique to simulator sickness (e.g., eyestrain, headache, visual aftereffects).

The prolonged effects of VIMS, such as spatial disorientation, postural instability, and other perceptual-motor disturbances, are particularly critical in terms of their implications for user safety and operational readiness. While relatively rare in present systems, these effects are sufficiently profound when they do occur that some U.S. Army and Navy training facilities have adopted mandatory grounding periods following simulator training sessions. These effects _may_ increase in frequency and severity when more sophisticated VR systems for training and mission rehearsal begin to come on-line. Although these systems may prove to provide excellent training and mission rehearsal in most respects, their utility will be limited to the extent that individuals are incapacitated by their use. Therefore it is critical to identify the factors that promote the occurrence of VIMS in these systems so that their full potential can be realized.

VIRTUAL REALITY AND SICKNESS

A large body of research exists which indicates that motion sickness can be induced in stationary observers (e.g., Andersen & Braunstein, 1985; Hettinger et al., 1990; Lestienne, Soechting, & Berthoz, 1977; Sharkey & McCauley, 1991). The common finding among all these investigations is that sickness occurs when the observer experiences a highly compelling illusion of self-motion referred to as "vection." While the connection between vection and visually-induced motion sickness has been apparent for some time, there has been little research conducted to date designed to isolate the stimulus factors that underlie this phenomenon.

The occurrence of VIMS poses signficant problems for the development of highly realistic simulation technologies such as VR. One of the principal goals of VR is to provide the user with a compelling illusion of "felt presence" in the simulated environment or "virtual world." A significant aspect of this felt presence involves illusions of self-motion which will almost certainly prove to be more compelling in future systems than those experienced in current simulators. VR may also lead to disruptions in normal postural control strategies, a factor that may also promote the occurrence of VIMS (Riccio & Hettinger, 1991; Riccio & Stoffregen, 1991).

RESEARCH ISSUES

There is a significant need for research to identify the factors that promote VIMS in order to alleviate the problem while VR systems are in the development phase. However, the literature on VIMS and simulator sickness indicates that there are multiple factors that may contribute to the phenomenon, as well as multiple, idosyncratic manifestations of sickness (Kennedy & Fowlkes, 1990). These characteristics of VIMS make empirical investigation a difficult matter.

Based on the results of experiments that have demonstrated relations between vection and sickness (e.g., Cheung et al., 1991, Hettinger et al., 1990) it is reasonable to hypothesize that any visual display factors that enhance the experience of illusory self-motion will increase the probability of sickness in VR systems. These may include factors such as field-of-view, spatial frequency content of the visual display, and optical flow and/or edge rate. Sharkey and McCauley (1991), for instance, observed significant effects of optical flow rate on the incidence of sickness in a fixed-base helicopter simulator. High rates of optical flow resulted in significantly higher rates of sickness. It is unclear at this point whether optical flow exerts it effect on sickness by enhancing the illusion of vection, by altering postural control strategies, or perhaps through some other mechanism.

An explanatory model of VIMS would be incomplete without taking account of operator control behavior (Hettinger, Kennedy, & Riccio, in preparation). The motion pattern which an individual views in a simulator and in current VR systems is to a large extent determined by the control inputs which that individual introduces to the system. Experienced operators can be expected to introduce finer, more precise control inputs while novice operators can be expected to introduce more variable, less precise control inputs. The nature of operator control activity is likely to affect the probability of occurrence of motion sickness symptomatology both for the operator and for other individuals within view of the visual display.

INTERIM RECOMMENDATIONS

Until the necessary research can be conducted to provide design recommendations to alleviate the occurrence of motion sickness in VR systems, an interim solution may lie in the judicious use of this technology (McCauley & Sharkey, 1991). As part of the U.S. Navy's program of research on simulator sickness, a set of guidelines for simulator use to alleviate the problem was developed (Kennedy et al., 1987). These guidelines may also prove to be beneficial to users of future VR systems.

The key recommendation for the use of these systems may be to take advantage of the human capacity for adaptation to altered or rearranged visual perception (Welch, 1978). Simulator sickness research indicates that incapacitation is most likely to occur during initial exposures to a novel simulator (e.g., Uliano et al., 1986) or simulator scenario, particularly when there is a high level of apparent motion present (e.g., high rates of optical flow, frequent changes in acceleration). By minimizing the level of activity in early exposures to VR systems, one increases the likelihood that adaptation will guard against subsequent problems with sickness.

CONCLUSIONS

Research that has been conducted to date strongly suggests that future VR systems for flight simulation and mission rehearsal may produce high levels of motion sickness. This prediction is made on the basis of the observation that VIMS tends to occur most frequently in those situations in which individuals experience highly compelling illusions of self-motion in the absence of actual physical displacement. VR technology seeks to maximize the felt presence of the user in a virtual environment, including the phenomenological concomitants of self-motion. An undesired side-effect of this high degree of realism may be an unacceptably high rate of sickness.

Recent research indicates that those factors that enhance illusions of self-motion and affect postural control activity may be the critical elements in VIMS. To the extent that we are able to better understand the contribution of these factors to the problem, it may be possible to influence the design of VR systems to minimize

its occurrence. In the meantime, the only effective approach to the problem may lie in the cautious use of the technology.

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THE EFFECT OF VISION ON MANUAL CONTROL AND SPATIAL ORIENTATION

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The overall objective of this research is to determine how ambient visual information affects spatial orientation and its perceptual (e.g., vection) and motor (e.g., postural and manual control) concomitants. Previous research has shown a relationship between whole-body vection (V) and visually induced postural change, although the latter's onset occurs considerably before the perceptual experience of self-motion opposite to the moving scene. Although visually induced manual and postural changes exhibit many similarities, they appear to differ in their frequency response and in other respects. Since little research exists concerning how ambient vision affects manual control (MC)--despite the fact that it represents the motor system used by the pilot to control the aircraft--we have focused upon this system in our own research. We also have assessed the effects of visual scenes on the somatogravic illusion (SGI), a major source of spatial disorientation mishaps.

In the first study, we investigated which sectors of the visual field most greatly affect MC, V, and induced motion (IM) of a central attitude display opposite to a moving background (i.e., the Duncker illusion). Previous research (Heckman & Howard, Perception, 1991; in press) suggests that whereas V is dominated by far visual motion, IM may be more influenced by visual motion in the same plane as the stationary central display. We have hypothesized that the bias of the stick in the direction of background scene

motion during MC tasks may be more related to the attempt of the subject to "null" preconsciously perceived IM than to a compensation for V. Hence, manual biases are hypothesized to be dominated by the same sectors of the visual field that give rise to IM rather than V.

In one experiment, twelve subjects viewed a 54 x 44 deg visual image that was composed of 50 dots moving in the roll plane at a velocity of 25 deg/s. Subjects viewed the dots while they tried to keep an unstable centrally located target that resembled an attitude display at a "wings-level" position. The background dots were located either in the same depth plane as the fixated central display, or 16 cm in front of or behind it. In some conditions, the dots moved in a single plane, whereas in others they moved in different depth planes in opposite directions. In a second experiment, the background roll motion involved a total of 80 squares which were located in the same depth plane as the "attitude" display, but which were confined to either the central (0-57 deg) or peripheral (58-115 deg) visual field . As in the first experiment, the texture elements moved in the same direction on some trials, and in conflict with one another on the others. In both experiments, the manual bias of the stick was calculated, along with subjects' ratings of V and IM.

The results of the initial experiment showed that both IM and MC biases were strongly elicited by the coplanar and far dots, but were dominated by the far dots in the coplanar-far conflict condition. Conversely, image motion in front of the fixated central display had much less effect, either in the conflict conditions or in isolation. Unfortunately, the small visual field used in the depth experiment may have impaired the perception of V, which was not significantly different from zero in any condition. In fact, the results of the eccentricity experiment revealed that V is almost completely dependent

on the peripheral visual field stimulation, with very little self-motion reported during the central condition. As expected from the first experiment, however, central roll motion produced both good MC biases and IM.

In combination, the results of the two laboratory studies suggest that MC biases are highly related to the experience of IM, but may differ in some respects from V and postural change, which involve whole-body perceptual-motor reactions. Contrary to previous research, however, it appears that all of these visual orientational percepts are dominated by far visual inputs, presumably because large-scale motion in near vision (i.e., peripersonal space) is not a reliable indicator of self-motion. But far visual dominance may also arise because we typically encounter nearer objects against a more distant visual background during MC and the oculomotor processes associated with it (Previc, Behav Brain Sci 1990; 13:519-542).

The above laboratory results may be relevant for understanding the findings of a second study that investigated visual scene influences over the SGI. The SGI occurs whenever an inertial force created by takeoff or other aircraft acceleration is misconstrued as a shift of the aircraft's position relative to gravity. In the presence of reliable visual information, the pilot almost never experiences the SGI, because he is able to correctly attribute the inertial force to the aircraft acceleration and thereby dissociate it from the sustained gravity vector.

We conducted this experiment in the Armstrong Laboratory's Vertifuge, which produced an SGI of 30 deg by means of centripetal acceleration (5.67 m/s^2) and its consequent centrifugal force directed in the $+G_x$ direction (i.e., toward the front of the subject). Nine subjects (seven of whom were pilots) viewed head-fixed helmet-mounted visual scenes that subtended 90 x 60 deg and depicted visual acceleration over a shoreline for 30. The scenes were

composed of various cues in isolation and in combination, including texture, horizon, perspective, and color. Subjects indicated their perceived position of "down" during the final 7 s of each trial using a down-pointer, and also rated the magnitude of linear V induced by each scene.

No significant reduction in the SGI was observed in the eight visual conditions relative to the eyes-closed condition. However, an overall reduction in the SGI of at least 20% was observed in four of the nine subjects. Modest V was experienced in the visual conditions that included texture flow, but V was not correlated with the ability of the various scenes to reduce the SGI, even in those subjects that showed the greatest visual effects.

Because the scenes were head-fixed--even though subjects' heads were loosely restrained and head movements were kept to a minimum--and because of other optical distortions and limitations, subjects did not perceive the visual scenes as adequately representing the out-the-window visual world. Based on the laboratory findings with MC, IM, and V, one of the most critical factors may be the perceived depth of the visual scene. Had our scene truly appeared to emanate from a great distance beyond the cockpit, it would have likely produced a much greater reduction of the SGI.

FLIGHT SIMULATOR SIDE EFFECTS AND VISUAL DISPLAYS EVALUATION

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Objectives:

The primary purpose of the investigation was to determine the frequency and severity of simulator sickness occurrences associated with the use of the Display for Advanced Research and Training (DART) and the Limited Field-of-View Dome (LFOVD) visual simulation systems during normal flight operations. A subjective visual display evaluation of the two systems was conducted as a secondary objective to identify any significant display deficiencies.

Problem:

The Dart and LFOVD visual simulation systems, which are located at the Armstrong Laboratory, Aircrew Training Research Division (AL/AZ), were acquired to provide advanced testbeds for the development of flight simulator visual system design specifications. Following some recent demonstration flights, however, physiological side effects were reported in conjunction with the use of the DART visual system. To determine if simulator sickness might be a persistent and debilitating problem for DART users during normal simulator operations, the present study was conducted. The LFOVD visual simulation system was included in the evaluation to compare the incidence of simulator sickness between the two visual displays.

Additionally, the design characteristics of neither visual display had been subjected to a systematic engineering or behavioral evaluation. It appeared this investigation would provide an ideal opportunity to concurrently conduct such an evaluation. Further, because the properties of the displays could influence the incidence of simulator sickness, as well as the utility of the visual systems in R&D programs, it appeared information from such a display evaluation could enhance the simulator sickness investigation.

Method:

a. Equipment

The DART and the LFOVD visual simulation systems were used in the study. The DART provides a mosaic of eight pentagonal rear-projection screens that surround a simulated F-16 cockpit. Computer generated imagery is projected onto the screens with commercial BARCO Electronic, cathode ray tube (CRT) projectors. The eye-to-screen distance is 37.5 inches, and the total field-of-view (FOV) is 300 degrees horizontal by 200 degrees vertical.

The LFOVD employs a head-coupled area-of-interest (AOI) display that includes a high-resolution inset surrounded by a low resolution wide-angle background providing an instantaneous FOV of 140 degrees horizontal by 60 degrees vertical. The Field-of-Regard is approximately 320 degrees horizontal by 120 degrees vertical. The computer generated imagery is the same used by the DART, and is projected onto the inside surface of a 24-ft.-diameter dome with General Electric light-valve projectors. A fully operational F-16A simulator cockpit is enclosed in the dome.

b. Subjects

A total of 16 active duty U.S. Air Force T-37 and T-38 undergraduate pilot training instructor pilots (IPs) were used as a first phase to the study. The second phase included a group of eight current or former military pilots, who either had not recently flown or were retired from military flying.

c. Experimental procedures

Each pilot subject was tested twice, once in the DART, and once in the LFOVD, with at least a two week interval between each flight. In each test, the pilots accomplished: (a) a 5-minute simulator familiarization flight, (b) a 5-minute practice formation flight, (c) a 20-minute low-altitude, single-ship road reconnaissance flight, (d) a 20-minute low-altitude formation flight. All segments of flight took place in a narrow, winding canyon with abrupt turns. A motion history, and physiological status questionnaire were completed by each pilot before they flew. Additionally, all pilots were asked for a comfort rating on a scale of 1-7 every five minutes during the 50 minute flying session, and objective performance measures such as altitude, airspeed, roll rate, etc. were collected. Equilibrium tests, and symptom checklists were also completed before, immediately after, and 30 minutes after each flight.

A subjective displays assessment was conducted concurrently with the simulator sickness evaluation to identify adequacy of the visual systems and to specify display deficiencies. For the displays assessment, the participants were asked a series of display related questions about the quality of the visual system during the simulated flights. In addition, they were asked to rate a wide range of visual display characteristics upon

completing their flight and describe any display deficiencies they observed.

Results:

Since data collection was not completed until 11 SEP 91 only limited, preliminary results are available. Some of them are: (1) Of the 16 IPs who flew both simulators, only one experienced simulator sickness symptoms in either simulator to the extent that they could not complete the 50 minutes of flight. This person was forced to end the mission prematurely in both simulators, stopping at 16:16 minutes of flight in the DART and at 38:55 minutes of flight in the LFOVD; (2) Of the 8 pilots in phase 2, three were unable to complete 50 minutes of flight in the DART due to simulator sickness, stopping at 12:17, 24:52, and 26:42 minutes of flight. Two of the three individuals who did not complete the mission in the DART were also unable to complete the 50 minutes of flight in the LFOVD due to simulator sickness, stopping at 16:56, and 30:00 minutes of flight.

Preliminary inspection of the symptom checklists completed by each pilot seem to indicate no difference in the symptoms experienced by the pilots in the DART or LFOVD. It also appears that cases of severe simulator sickness are due to individual susceptibility not to simulator type in this instance. Finally, as can be seen in attached Figures 1 and 2, the mean comfort rating for each simulator is very similar; the ratings also appear relatively low, with a "1" on the comfort scale symbolizing no discomfort caused by the simulator, and "7" symbolizing severe discomfort.

Work Remaining:

Data analysis will be completed and a Technical Report will be published.

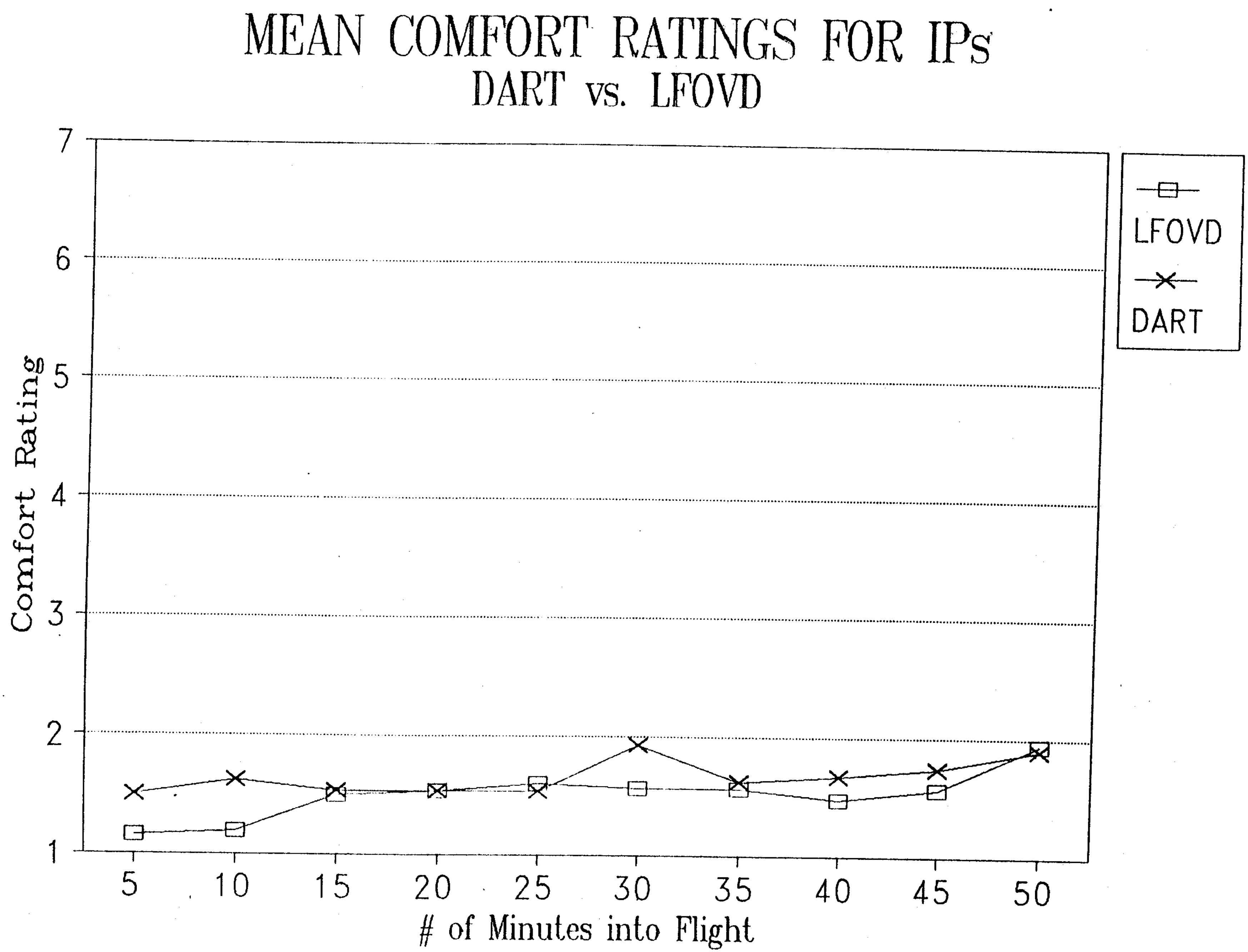
MEAN COMFORT RATINGS FOR IPs
DART vs. LFOVD
Comfort Rating
7
6
5
4
3
2
1
5
10
15
20
25
30
35
40
45
50
# of Minutes into Flight
LFOVD
DART

Figure 1

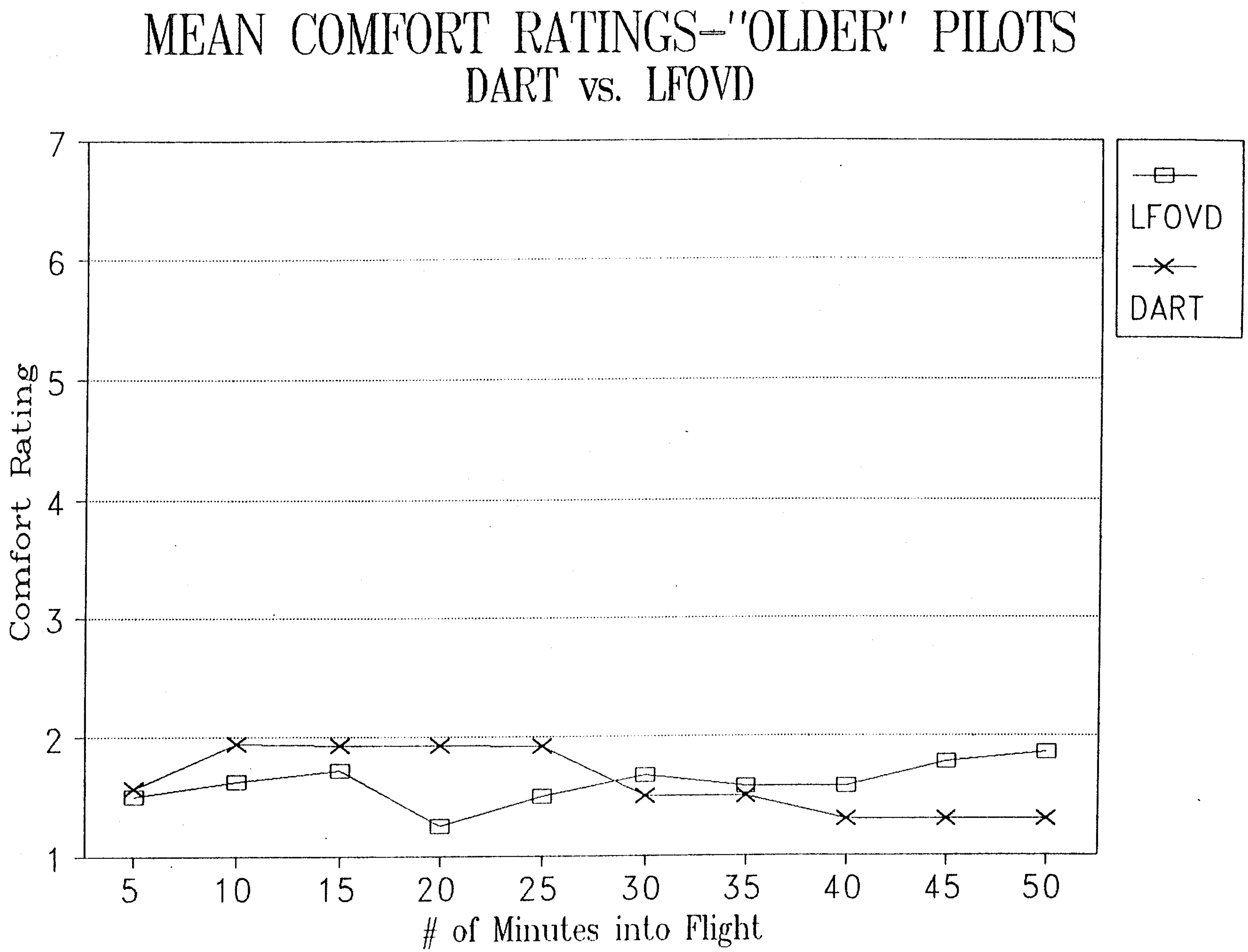
MEAN COMFORT RATINGS-"OLDER" PILOTS
DART vs. LFOVD
Comfort Rating
7
6
5
4
3
2
1
5
10
15
20
25
30
35
40
45
50
# of Minutes into Flight
LFOVD
DART

Figure 2

FLIGHT SIMULATION VISUAL RESEARCH BY THE CREW STATION RESEARCH AND DEVELOPMENT BRANCH OF U.S. ARMY NASA AMES RESEARCH CENTER, MOFFETT FIELD, CALIFORNIA

Robert T. Hennessy
Monterey Technologies, Inc.

The Crew Station Research and Development Branch (CSRDB) operates the Crew Station Research and Development Facility (CSRDB), a state-of-the-art, full-mission, military helicopter simulator. The CSRDF crew station comprises a CAE Wide-Field-of-View, Helmet Mounted Display, (WFOVHMD) two cockpits with color, touch-screen displays, two four-axis hand controllers per cockpit, and a speech recognition and production system. Other elements of the facility include three support stations to control other friendly and hostile aircraft, a central station to simulate headquarters and multiple other ground units via radio communications, and a complex model of air-defense weapons and ground vehicles.

The WFOVHMD has a field of view of 120 degrees horizontally by 60 degrees vertically. The resolution is 5 - 6 minutes of arc. A high resolution inset, 24 degrees horizontally by 19 degrees vertically has a resolution of 2 minutes of arc or better. Luminance is greater than 30 foot-Lamberts. The infra-red head tracking system allows an unlimited field of regard and more than one foot of translatory head movement in any direction.

The CSRDB research staff has performed a number of studies ranging in complexity from two-hour, full-mission studies involving multiple aircraft to tracking of air targets for 25 seconds. The following describes three recently completed studies directly bearing on visual simulation. Future plans are also surveyed.

Cue Augmentation for Night Vision Detection of Obstacles (CANDO)

During the build-up of U.S. forces in Saudi Arabia preceding operation Desert Storm, several helicopters were lost during night operations when the crew was using Night Vision Goggles (NVGs). The primary cause is thought to be loss of contrast among the sand dunes that prevented the pilots from detecting rising terrain. The U.S. Army Aviation Systems Command (AVSCOM) began to seek short-term solutions to the Saudi night pilotage problem. The Army Center for Night Vision and Electro-Optics (CNVEO) recommended the use of two narrow-beam aiming lights as an immediate expedient to provide terrain cuing in the sand dunes of Saudi Arabia.

The two lights, arranged vertically, are attached to a skid strut. The top and bottom lights are aimed with a 1.0 degree and 5.0 degree depression angle, respectively, from an assumed level flight path. Approximate visibility range of the lights is said to be about 300 meters. When the top light "disappears" it indicates there is no high terrain within several hundred meters. When the top light is visible, there may or may not be terrain high enough to be a collision hazard. The basic utility of this type of terrain warning and the efficacy of the cuing lights over a range of airspeeds, altitudes and visibility conditions was not established in the field trials. Moreover, since the visibility and time-to-collision warning of the lights are sensitive to the specific angles of the cuing lights, it is important to determine the appropriate angles.

In November, 1990, The U.S. Army Aeroflightdynamics Directorate (AFDD) initiated a program of simulation using the CSRDF to determine the efficacy of Cuing Augmentation for NVG Detection of Obstacles (CANDO). The CSRDF was modified to represent the essential characteristics of NVGs by masking each eye channel to provide a circular, 40 degree field of view, and rendering the scene in monochrome green. The high-resolution inset was not used. Geographic areas and environmental lighting conditions were chosen to produce marginally visible terrain with some of the features of Saudi Arabian desert, i.e., no vegetation and rolling terrain. The simulation of the cuing lights required parallel processing on a separate computer, holding a reduced visual data base, to determine the terrain intercept points of the lights.

Between November 1990 and May 1991 over 70 different combinations of cuing lights, altitude and speed profiles, and visibility conditions were simulated in the CSRDF. The cuing light arrangements were evaluated in short night mission flight profiles to determine the collision warning lead-time afforded to the pilots, ease of interpretability, and workload associated with each of the cuing light arrangements.

In the last evaluation series, four of the most promising light configurations were evaluated using six U.S. Army rotary wing pilots. The four configurations are called the Vertical (2 lights), the Horizontal (2 lights), the T-Cross (10 lights) and the SLICK-3 (7 lights). Changes in the relative position of the lights, as well as the number of lights visible, indicated whether the terrain was rising, level, or dropping. A no-light condition was also used as a control. The primary measure was ratings by the pilots on usefulness and ease of interpretation. Number of crashes, and altitude maintenance were also used as measures.

The number of total crashes was to low to be statistically useful. The altitude measures have not been fully analyzed. The subjective ratings were found to be statistically reliable. Pilots rated the SLICK-3 and Vertical configurations more useful

than the other two. The Horizontal configuration was rated as less interpretable than the other three configurations which were not distinguishable among themselves in interpretability. Pilot commented that except for the Vertical arrangement, the cuing lights were aimed too far forward (200 - 300 meters) to be useful.

<u>Studies of Simulator Sickness</u>

A common problem in flight simulation is the occurrence of simulator sickness. The symptoms of this malaise are similar to those of motion sickness and include pallor, sweating, nausea, and vomiting. Multiple factors are thought to contribute to simulator sickness. Asynchrony between the visual display and movement of the motion base, when one is present, visual distortions, e.g., off-access viewing, inappropriate motion-base algorithms, simple delay in the visual system, and field of view size. The overall incidence of symptoms is low, about 40%, and the frequency of extreme symptoms is much lower. Because the physiological mechanisms are poorly understood and the incidence is low, simulator sickness is a difficult phenomenon to study experimentally. However, some successful work has recently been accomplished by the CSRDB.

Simulator Induced Alteration of Head Movements (SIAHM) In the early seventies, concern was expressed about the relatively small Field of View (FOV) of many military flight training simulators. The concern was that the pilots would learn not to scan by moving their head because there was no scene except on the central 48 by 36 degree display. The major problem was that the learned bad habit may transfer to aircraft. This concern has evaporated with the advent of wide FOV displays. More recently, a concern was expressed that pilots suffering from simulator sickness may not move their heads in an attempt to ameliorate the symptoms. The problem is, again, that this behavior may transfer to flight in the actual aircraft.

During March and April 1991 a study was performed at the CSRDB to determine if simulated flight (presumably inducing simulator sickness) would cause a subsequent alteration of head movements in an actual aircraft. The design was simple. Six Army pilots performed two maneuvers over a taxiway on one day, performed the same maneuvers in the simulator the next day, before a chase intended to induce simulator sickness, and then performed the same maneuvers again afterwards. The pilot then went straight to the flightline outside and repeated the maneuvers in the helicopter. Head movements could be measured in both the simulator and the aircraft. Ratings of simulator sickness were taken before and after each real flight as well as before, during and after the simulation flight.

The two test maneuvers were designed to involve substantial head movements. The first maneuver, called the Sawtooth required the pilot to move laterally across the taxiway to the left to

arrive over a taxiway light. The pilot then reversed course, and moved laterally, and forward, to the next taxiway light on the light. During the entire maneuver the pilot was to maintain heading aligned with the taxiway. The maneuver continued for ten pairs of taxiway lights. The pilot then flew straight back to the starting point and repeated the maneuver for a second time. The second maneuver, called the S-turn, required the pilot to do a series of S-turns passing across each pair of taxiway lights a 90 degree angle to the taxiway. This maneuver was performed immediately after the Sawtooth maneuver and was also performed twice. The maneuvers were performed in a AH-1 Cobra helicopter with a safety pilot occupying the front seat.

The same pattern of maneuvers was performed the next day in the CSRDF. The pilot then chased another helicopter following a pre-recorded flight path for about twelve minutes. The Sawtooth and S-turn maneuvers were then repeated in the simulator. Within ten minutes, the pilot was in the Cobra helicopter doing the same two maneuvers.

The results were interesting. The two maneuvers developed to test the head-movement hypothesis were found to be extremely nauseogenic in the simulator. None of the pilots were able to complete the full simulator flight sequence. All voluntarily terminated the flight due to the imminent chance of vomiting. The chase maneuver, intended to induce simulator sickness, was reported by the pilots to be a relief. The Sawtooth and S-turn maneuvers did not produce any reported symptoms in the aircraft. Although all the pilots had to terminate the simulator flight, each was able to continue to the actual flight maneuvers on the second day. Apparently the few minutes between the simulator and actual flight, plus the short walk across the flightline were enough to reduce the symptoms to the point that the flight maneuvers could be performed.

The head movement data from the before and after flights in the simulator have been graphed for inspection but not quantitatively analyzed. However, even from inspection it is clear that the amplitude of head movements was much reduced in the after-simulation flight relative to the pre-simulation flight. In other words, the data appear to support the hypothesis that simulator sickness, or at least, the simulator experiences described previously, do influence head movements. However, a control is needed to rule out order effects.

This study accomplished quite a bit. It was the first study of simulator sickness to demonstrate that the sickness occurs only in the simulator and not in the aircraft. Second, the SIAHM maneuvers were discovered to be reliable inducers of simulator sickness. Heretofore, the chance of various maneuvers inducing simulator sickness was small. In the future, these maneuvers can be used to induce simulator sickness to study other independent variables. Third, while tentative, the results show that

simulator sickness may have deleterious effects of operational significance.

Quantification of Visual Flow. Investigating simulator sickness has been difficult on both practical and theoretical levels. The SIAHM work addressed some of the practical difficulties. This study addressed a more theoretical issue - how to measure the independent variables.

Both the Committee on Human Factors of the National Research Council and NASA have sponsored meetings to exchange data and elicit opinions from experts in simulation and motion sickness. The most prevalent conclusion is that simulator sickness occurs because there is a conflict between visual cues and body-sense, primarily vestibular, cues that give rise to the perception of self-motion. In a real aircraft, or other vehicle, the visual and body cues are in harmony. Changes in direction and speed of motion are signalled consistently by both systems. In a simulator, however, the harmony is disrupted because continuous changes in direction and speed cannot be sustained by the motion base. Moreover, many simulators have no motion system because the visual system alone is thought to provide sufficient cues to self-motion.

As attractive as the cue conflict hypothesis may be, no one knows how to define cue conflict quantitatively. In a fixed-based simulator, such as the CSRDF, the body-sense cue must be zero. If the visual cue to motion could be quantified in some way, it would be a start for defining cue conflict. To this end a study was conducted using the CSRDF to determine if a measure called Global Visual Flow (GVF) would correlate subjective, performance, and physiological measures of simulator sickness.

In the CSRDF, angular visual flow, and changes in visual flow, are governed by the speed, altitude and maneuvering of the aircraft. Global Visual Flow is operationally defined as the ratio of the eye height divided by airspeed. In the experiment, called VISFLOW, 16 Army rotary-wing pilots were required to chase a maneuvering lead aircraft for approximately 45 minutes. The movement of the lead aircraft was produced by a replay of a flight path flown by another army pilot. The chase course was flown by each of the participating pilots at a high (400 ft.) and low (100 ft.) altitude.

During each run the aircraft positions, velocities and accelerations were recorded. Similar measures were recorded for the pilot's head position. Also, before, during and after the run each pilot provided a self-report of discomfort on a one to seven scale. Before and after each run, tests of postural equilibrium were administered. Physiological measures were taken from each pilot. These included heart rate, vagal tone, respiration rate, skin conductance and temperature, peripheral blood flow and an electrogastrogram (EGG) measure of stomach motility.

The results showed that there was a significant relationship between the GVF index and subjective ratings of pilot discomfort. On the seven point scale subjective discomfort was about three for the high altitude, low GVF value, and about five for the low altitude, high GVF value. None of the postural equilibrium measures showed any differences as a function of GVF. Interestingly, the Electrogastrogram (EGG) measure of stomach motility was significantly related to subjective discomfort. However, average values do not give a complete picture. The measure is highly idiosyncratic. For some individuals there is a high correlation between EGG and discomfort, while for others there is almost none.

Work on quantification of cue conflict will continue. In the fall of 1991, a simulator sickness study will be performed using the vertical motion simulator at NASA Ames Research Center. In this study the SIAHM maneuvers, which were found to be highly nauseogenic will be flown with and without the motion base active to determine how much motion, per se, contributes to the presence or absence of simulator sickness.

<u>Future Plans</u>

Visually related research is planned for the future. At present, a study of air-to-air tracking, using head and hand is underway. Unconventional displays of sensor images will be evaluated for their efficacy in initially acquiring and maintaining track of targets. An interesting side development, now nearly complete, is an acoustic head tracker and display for laboratory use.

Northrop Corporation is developing a sensor for Army helicopters that can detect wires and other flight obstacles. The CSRDB is tasked with development of symbology, or other means, for informing the pilot of the output from the Obstacle Avoidance System (OASYS).

In cooperation with the Aerospace Human Factors Division at NASA Ames Research Center, a study of the effect of stereopsis on performance of helicopter flight maneuvering will be conducted early in 1992.

CUING AND SCENE CONTENT REQUIREMENTS FOR LOW-LEVEL FLIGHT

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Pilots flying at low altitudes rely heavily on out-of-the-cockpit visual cues to control altitude and avoid contact with the terrain surface. A fundamentally important component of any flight simulator designed for training low-level flight skills is the image of the world displayed to pilots. Computer image generators (CIGs) of the recent past (as well as inexpensive graphics workstations available today) were limited to a relatively small number of surfaces that could be displayed at any given time, and lacked sophisticated texturing capabilities now available with state-of-the-art CIGs. It is of interest to note that even simple scenes composed of large triangular or rectangular terrain faces populated with a few simple three-dimensional objects provide sufficient visual cue information for pilots to perform various tasks with some minimal level of competence. The present research addresses the question of how simple scenes may be enhanced using current CIG technology.

An important consideration is that, despite current technological sophistication, CIGs remain limited-capacity processors. An increase in one type of simulator scene detail may be offset by a decrease in another. One line of research being pursued at the Aircrew Training Research Division of the Armstrong Laboratory investigates possible tradeoffs among various types of simulator scene detail. Previous experiments show that performance of a variety of low-level flight tasks improves with increases in the density of three-dimension objects in a simulator scene. To optimize density, objects have frequently been simple in shape. For example, three-sided pyramids, or tetrahedrons (the simplest three-dimensional shape), are common. One question concerns whether cue effectiveness increases when objects are made more detailed and realistic in appearance. Results to date consistently show that detection of change in altitude is no better with detailed/realistic objects than with simple tetrahedrons. Performance improves with increases in object density, however, up to the maximum possible level of 175 objects/square mile. As realistic objects are more demanding of CIG processing than tetrahedrons, available resources may be used most effectively by maximizing object density rather than object detail/realism.

In a recent investigation, object detail/realism and object density were evaluated in the context of a complex cell texture pattern on the terrain surface. As before, no advantage was obtained for detailed/realistic objects. Performance did improve with complex texture on the terrain surface. Although texture alleviated poor performance at low object densities to some extent, best performance was still obtained with the highest density of 175 objects per square mile. Complex texture appears to be most

effective when used on terrain surfaces rather than on individual objects. However, texture does not eliminate the need for high levels of object density.

The above approach may be conceived as a process of building up simulator scenes by adding features that have proven to be effective. An alternative is to ask, first, which features of real-world terrain are salient to pilots during low-level flight. An effort is currently underway to analyze photographic imagery of real-world terrain using a multidimensional scaling (MDS) technique. Pilots rate the visual similarity of a variety of real-world terrains depicted in photographic imagery of actual low-level flight. Ratings are submitted to an MDS analysis which yields as output a spatial mapping of terrains such that terrains judged to be similar are positioned close to one another in space whereas dissimilar terrains are positioned farther apart. Subsequent examination of the features of terrains positioned near one another in space provides information as to which features are salient to pilots.

Results thus far provide consistent evidence that pilots are sensitive to two essential aspects of terrain: 1) terrain contour and 2) object size and spacing. The important element of terrain contour is the presence/absence of hills and ridges rather than large mountains obstructing the horizon. Such features are not commonly seen in simulator scenes and have not been previously evaluated. Pilots are most sensitive to tall objects with considerable horizontal extent, that is, large buildings or groups of trees clustered closely together and separated by open spaces. Interestingly, terrains with a uniform distribution of objects similar to those used in simulator investigations were positioned nearer terrains with no objects. The optimal spatial arrangement of objects, therefore, appears to be discontinuous.

Multidimensional scaling analyses have been performed using subjects with a variety of backgrounds (including non-pilots) to determine the role of prior experience on sensitivity to terrain features. Surprisingly, the same pattern of results has been obtained with each group. The terrain features captured by this analysis, therefore, do not appear to reflect information learned during actual low-altitude flight. This is not to deny that perceptual learning occurs as pilots become more proficient at low-level flight. Rather, it suggests that learning either centers on the efficiency with which cues are used or, possibly, learning of idiosyncratic cues specific to terrains over which pilots routinely fly.

Taken together, these results support three main conclusions: 1) Three-dimensional features such as hills and tall objects are most important; 2) Although high object density is important, the optimal spatial distribution of objects is discontinuous suggesting that grouping may be a factor; and 3) Complex texture is most useful when applied to large surfaces such as terrain faces.

Scene Related Optical Information Potentially Important for Flight Control

Walter W. Johnson
NASA Ames Research Center

Simulator validation and certification have, in general, not included scene content criteria. This may, in part, be due to the fact that fixed wing aircraft, in addition to being highly instrumented, tend to operate at altitudes that are high enough that a basic horizon line and defined groundplane are all that is needed. The main exception to this is, of course, during landing and takeoff, and much work has gone into creating highly realistic visual databases of airports. In addition, airports tend to have a relatively common structure, so generalization of training from simulated to actual airports is relatively assured.

On the other hand this is not the case for military fixed wing NOE and contour flights, nor for much civilian and military helicopter flight. These craft often operate close to the ground where they are controlled almost exclusively on the basis of the out-the-window scene. Additionally, helicopters fly near the ground in a large number of environments (e.g. emergency medical evacuations at accident scenes, rooftop vertiports, examining transmission lines and pipelines), not only in the highly predictable contexts of heliports or airports.

Another important distinction is that, in the majority of cases, civil training simulators have been used by major airlines to train pilots to navigate using VORs and other avionics-based positioning information. Thus navigational information is not being obtained from the visual scene. For the case of helicopters, and much light aircraft also, navigation is often based on the contents of the visual scene as sampled through the aircraft window. Pilots fly between visual landmarks, follow roads, go through valleys or along ridges, etc.

So guidance and control in helicopter and military simulators are more strongly impacted by scene content than has been the case for most previous civil simulators. Given this, good criteria for scene content still remains to be determined. One question that could be asked is if there is any good evidence that suggests scene content is important in simulation performance. The answer to this comes from both flight studies/flight reports, and from data obtained in simulator studies.

Perhaps the most recent evidence concerning the importance of scene content to flight performance comes from difficulties encountered by Army helicopter pilots in night flights during Operation Desert Storm. Despite the aid of night vision goggles, the nighttime desert presents a very textureless surface to pilots. As a result the pilots initially encountered much

difficulty until they learned to fly in these new conditions. Another major component to the problem was the loss of horizon, or a false horizon. Within dune fields the horizon would often be totally obscured, or the crest of some high dune would be mistaken for a true horizon line. This is similar to the classic "black hole" landing problem (night time landings where no usable horizon line exists), where pilots often encounter difficulties.

In the Rotorcraft Human Factors Research Branch at NASA Ames we have been examining how vehicle position and motion, together with the layout of the world (e.g. terrain, objects, texture) combine to produce optical patterns which pilots, in turn, can (and do) use to directly control their vehicles. Our approach has been to design vehicle control tasks in such a manner as to allow the experimental isolation and evaluation of the utility of various types of optical information. Thus we are quantifying both control activity, and the types of optical change made available by the visual scenario, and then using various techniques to evaluate which types of optical change the vehicle operator is attempting to regulate. Below some selected instances of this work, and its implications for specifying scene content criteria for helicopter simulations, is listed.

Speed Control

We have examined the perception and control of forward speed in a number of studies. In these studies we have manipulated **edge rate** (the frequency at which salient scene elements are being passed by), **flow rate** (the mean angular speed of optical elements), and **ground speed**. Previous studies have shown that people use both edge and flow rate information when making judgements about ground speed, but that edge rate tends to dominate (Owen, Wolpert, & Warren, 1983; Larish & Flach, 1990). These studies have been done in level flight over ground textures that may have contained insufficient, and possibly even conflicting cues to observer altitude. This presents a potential problem since edge rate varies with both ground speed and ground scene element density, or

$$\text{edge rate} = (\text{ground speed}) * (\text{element density})$$

while flow rate varies with both ground speed and altitude, or

$$\text{flow rate} = (\text{ground speed}) / (\text{altitude})$$

The consequence of these relationships is that a person must have information about ground element density or altitude in order to determine ground speed from edge or flow rate cues. Without good altitude cues it is difficult to determine if changes in optical density are due to altitude changes or to ground element spacing, and thus edge rate provides ambiguous ground speed information. Similarly, without good altitude cues it is difficult to determine if a changing flow rate is due to a ground speed change, or to an altitude change.

We have examined the ability to actively control ground speed while manipulating the presence/absence of changing flow rates, edge rates, ground speed, and both with and without good optical information about altitude. The results from these studies have confirmed previous findings showing a predisposition to use edge rate information to judge

and control ground speed, but have also shown that strong altitude cues will moderate this tendency when edge rate changes are coupled with ground element density changes and not with true ground speed changes.

Altitude Control

The perception and control of altitude during hover and during forward flight has been examined in a number of studies. For the case of hover we have conducted simulation studies showing that pilots will try to hold the optical positions of particular objects at a constant visual declination below the horizon (Johnson & Phatak ,1990). Other work at NASA has indicated that, during forward flight, optical element density is an important factor (Johnson, Tsang, Bennett, & Phatak, 1989).

Glideslope and Glideangle Control

The visually guided control of descent to a landing surface (helipad, runway) is being examined in a number of studies. Initial research on the control of descent to landing pads under black hole conditions has shown form ratio effects similar to those reported by Mertens and Lewis (1982), but has also shown that form ratio is insufficient to fully account for glideslope acquisition. Work is presently being conducted to try to isolate the optical scene content that accounts for the better than predicted performance.

The implications of much of the above work is that pilots often attend to, and learn to directly regulate, the two-dimensional cues of the visible scene. This is in contrast to the assumption that pilots react to the three-dimensional geometry which they have recovered through some type of inverse transformation. Thus learning to hover in the presence of towers will not generate the same skills as learning to hover over a more or less flat terrain. Similarly, learning to land a helicopter at an airport with a clearly visible horizon does not necessarily prepare one to learn to land a helicopter in a valley where there is no visible horizon.

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PERFORMANCE EFFECTS ON PILOT TASKS DURING FLIGHT IN A VIRTUAL WORLD

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Introduction

A structured visual environment (SVE) may be formed by a prominent window-like frame or by large, salient objects with sharply delineated edges. Such an environment may have a most dramatic influence on our perception of the world (Bischof, 1974; Dichgans and Brandt, 1978; Howard, 1982; Matin and Fox, 1989).

The data upon which such conclusions have been made range from purely psychological studies (Witkin and Asche, 1948; Rock, 1982; and, Stoper and Cohen, 1989) to high fidelity simulations of real world flight tasks (Kraft and Elworth, 1969).

Levelness. The studies examining the effects of SVE on performance have explicitly or implicitly categorized the concept of levelness into three different *perceptual* coordinate systems: gravity-, optical-, and head-referenced systems (GRS, ORS, and HRS). Each of the perceptual coordinate systems have a *physical* analog which is referenced to an inertial, euclidean, or physiological coordinate system, respectively.

All of the perceptual coordinate systems, as will be discussed, may be in registration, and coincide with their physical analogs. Such an instance would provide the basis for a conformal perception of the world. Or, under certain naturally occurring conditions, they may become misaligned. If such a situation occurs, the perception of the world may become ambiguous, with disorientation as a potential, inherent result.

Gravity-Referenced System. To specify the location of a target with respect to the GRS, information concerning (a) the retinal coordinates of an object, (b) the orientation of the eyes in the head, and (c) the rotational position of the gravitoception system with respect to earth gravity must be known. That is, the orientation of the retina must be specified with respect to the head; and, in turn, the orientation of the head must be specified with respect to the earth. If a person is standing erect, looking at the horizon, the orientation of the eyes, head, and earth correspond.

During flight, the GRS may become misaligned with respect to earth gravity. (See Figure 1.) A situation like this may occur during a constant rate turn, after the sensory effects of acceleration have diminished and the GRS becomes referenced to the force vector opposing lift. GRS may also become misaligned with earth gravity during forward acceleration ($+G_X$). Such sudden

$+G_X$ accelerations will result in the oculogravic perception that objects appear to rise above their true location (Cohen, 1977).

The force vector through the vertical axis of an observer ($+G_Z$) is normally coincident with earth's gravity. However, during a turn, $+G_Z$ will shift with respect to the earth's gravity vector, as the vestibular system adapts to the rotational acceleration. During such instances, the GRS will provide inaccurate information concerning earth's gravity, and a pilot will perceive that he is in straight and level flight, though he is still in a bank.

Optical-Referenced System. The static or dynamic perspective geometry of a scene specifies euclidean space. Static perspective geometry is typically depicted by various optical gradients such as size and density. Dynamic perspective geometry is additionally characterized by a velocity gradient, with texture elements closer to the observer having the greatest angular velocity.

Apart from the scene geometry, an observer's *perceptual* interpretation of the scene specifies the axes of the ORS. It might be expected that the ORS would always be in registration with the GRS. From a physical perspective, the optical world does coincide with the gravity specified inertial coordinate system. From a psychological perspective, however, the ORS, a perceptual system, may be in an orientation other than the GRS, another perceptual system. Such a situation can occur naturally during night flight, when ground lights may suggest a false horizon. See Figure 2.

Langewiesche (1944) suggested that glideslope control is maintained by regulating the distance between the runway aimpoint and the true horizon. This distance has also become to be known as the H-Distance (Berry, 1970; Cutting, 1986). However, environmental cues may provide an ambiguous interpretation of the magnitude of the H-Distance, as Kraft (1978) demonstrated. This ambiguity is the result of the ORS becoming distorted with respect to the true world, euclidean coordinate system.

Head-Referenced System. The basis for specifying the coordinates of the HRS are the vertical and horizontal meridians of the retina. If an observer's eyes are normal to the inertial and euclidean vertical axes, the typical perception is one of standing erect. Such is the case when a stationary observer is viewing the natural horizon. In order to determine the location of an object within the HRS, extra-retinal information is required, such as orientation of the eyes and inertial position of the head.

If the GRS and ORS are in registration, as would be the case in level, unaccelerated flight, the problem of resolving the location of a target within the HRS is essentially trivial. The problem exists when the GRS and ORS are not in registration. As was suggested earlier (e.g., Cohen, 1977), it is known that both the location of a target within the HRS, or the orientation of the HRS for that matter, may be independently influenced by the orientations of both the GRS and ORS. It is, then, when the GRS and ORS become misaligned with either each other, or their physical analog, that an observer must resolve the ambiguity to which of these two reference systems the HRS must coincide.

Problem Statement

Head-mounted, virtual world technologies were developed in the 1960's. Comeau and Bryan (1961) reported on a head-slaved video control system. In 1968, Sutherland discussed a head-slaved, graphics based virtual world that was later demonstrated by Vickers (1970). Operational systems for military aircraft were quickly developed and tested. (Johnson and Foster, 1977).

There are two primary purposes for head-mounted systems in aeronautical settings. One is for helmet-mounted flight displays and teleoperated (head-slaved) weapon systems. Bennett, Johnson, Perrone, and Phatak (1988) evaluated head-tracking performance during passive and controlled flight. In that study, comparisons were also made of head tracking performance in sterile and relatively complex virtual worlds. That study confirmed the robustness of head-tracking performance across a wide variety of visual scenes.

Early on in the development of head-mounted, virtual world displays, the capability existed to track all six head states, three translational and three rotational (Polhemus, 1976). Subsequently, designers apparently realized that the three translational axes of the head added little to the system performance, if the controller remained seated, as in a cockpit. Additionally, because the aiming or pointing accuracy of a system is not degraded when it is rolled, head roll need not be tracked. As a result, current displays, such as that used in the AH-64 helicopter has no roll-compensation. That is, when a pilot views the horizon while rolling his head, the horizon follows his eye-plane and does not remain perpendicular to gravity. In this case, the display is said to be image roll-stabilized; or, the display is without roll-compensation.

Purposes. There has been no rigorous evaluation of whether roll-compensation is a necessary requirement for the design of head-mounted displays that are used for tracking. *One purpose of this study was to conduct a trade-off analysis of the benefits of image roll-compensation, thus contributing to the design criteria for head-mounted displays.*

There is a large data base concerning the biases produced by SVEs on the judgement of roll (See Howard [1982] for reviews.). On the other hand, there have been comparatively few studies of the effects of SVEs on pitch judgements (Cohen and Stoper, 1989). Apparently, all of the studies on SVE have used discrete trial paradigms, during which both the observer and target were stationary. Apparently, there have been no studies of the affects of relative motion in SVEs on optical bias judgements. *A second purpose of this study was to quantify the bias effects of image roll-stabilization on smooth head pursuit.*

METHODS

A computer generated, perspective, wire-frame grid was displayed to five observers on a head-mounted, one-inch Sony electronic viewfinder, mounted in front of the observer's eyes. Head position was monitored by means of a Polhemus electromagnetic head-tracker. As subjects moved their heads, they were able to control the graphics of the virtual world. The sensation was one of actually being in and looking around a graphics world. The

instantaneous FOV was 20 x 18 degrees. The field-of-regard was 360 degrees. The observers were "flown" over the grid at a constant airspeed at two different altitudes. Positioned on the surface was a wire-frame cube. See Figure 3.

The target was offset to the left or right of the direction of travel by two different distances. The observer was instructed to track the target with a cross-hair generated on the middle of the display. The combinations of altitudes and offsets generated a set of optical (angular) velocities at which the target would move relative to the observer. Adjusted root mean square error (ARMSE) between the direct line-of-sight (LOS) to the target and visual LOS projection to the ground was computed.

The graphical roll axis was frozen during half of the trials, in a random order. The observers were not informed about the display differences. The effect of this operation was to fix the horizon line in the FOV of the display, so that even if the the observer rolled his head, the horizon did not move. Observers were debriefed after the trials to determine if they observed anything unusual about the displays.

RESULTS

Figure 4 shows the angular tracking error with and without graphical roll-compensation as a function of azimuth from the simulated vehicle to the target. Altitude or offset had no significant effect on target tracking ARMSE, and were collapsed within roll conditions.

Tracking error significantly increased ($p<0.001$) as a function of azimuth angle. The relevant variable here is the optical velocity of the target. As the observer approached the target, the angular velocity accelerated, given a constant ground speed. Roll-compensation was not associated with any significant differences in ARMSE ($p>0.4$).

Furthermore, the observers were unable to identify verbally any differences between the conditions that had roll stabilization, and those that did not. This was true, even though they were asked specifically about differences in the displays.

DISCUSSION

The results of this study are consistent with an earlier evaluation of target tracking performance of AH-64 helicopter pilots (Bennett, et al., 1987). In that study, target tracking errors of line and instructor pilots were approximately 15 milliradians (for normal tracking regimes), which is near the mechanical tolerance of the system. Additionally, the tracking performance of the pilots was equivalent in accuracy to that of non-pilots (using comparable optical variables) with a system similar to the one used in the current study.

When the ORS and GRS become decoupled, the perceptual system must resolve the ambiguity forced on the HRS (Cohen and Stoper, 1989; Matin and Fox, 1989). Using discrete trial paradigms and static positions of the target and observer, it appears that the ORS will bias judgements, up to a point. As

discussed in the introduction, during flight the ORS and GRS will decouple and generate orientation illusions. In static settings (See above.), bias of optical judgements, or how the HRS will resolve the ambiguity, is dependent on the magnitude of the discrepancy between the ORS and GRS. The influence of the optical system diminishes with larger differences from the gravity system. During smooth pursuit head-tracking, the ORS dominates the GRS.

It appears, based on the data reported here, that optical roll variables play little importance in the control of head-tracking performance. This conclusion is further supported by the fact that not one of the subjects could verbalize the differences between the roll compensated and non-compensated displays.

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VISION RESEARCH AT AL/OEDL - AN OVERVIEW

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The goal of the Occupational and Environmental Health Directorate, Directed Energy Division of the Armstrong Laboratory is to assess the occupational impact of directed energy systems and extend electromagnetic bioeffects technology. The Laser Branch deals specifically with studying the effects of laser systems. The most significant effects of the relatively low energy laser systems in an operational environment are visual. Therefore, vision research related to the effects of laser energy is one of the primary efforts in this laboratory. An overview of the labs program areas and some of the ongoing vision research projects will be given. Specifically, the Counter Target Acquisition System Phase 2 (CTAS-2) program will be briefly discussed and a brief video describing this exercise will be shown.

The laser program may be divided into 5 major areas: operational support, optical countermeasures, optical counter-counter measures, health and safety, medical diagnosis and treatment. There is some overlap between these areas and they are not clearly separable.

Operational support is directed toward solving immediate problems of the users, operational units in the Air Force. Hazard assessments are made of military laser systems. The eyewear to protect against laser hazards is quality tested and evaluated. We provide consultations and make recommendations concerning the use of laser systems and laser eye protection. Accidents and incidents involving lasers are investigated. Support in the form of laser safety and awareness instruction is also provided.

Optical countermeasures is concerned with quantifying glare, flashblindness, and laser lesions from minimal to hemorrhagic and the resulting performance decrements. Simulation and image processing are two tools which are used in this research in this area to gain an understanding of these issues.

The optical counter-countermeasures program primarily deals with eye protection from lasers. Specific visors and other eye protection are tested to determine their optical density for specific wavelengths, other optical properties, damage thresholds, comfort, and the possible effects of the visors themselves on vision.

Health and safety is a fourth main area. A major program is developing to assess the damage mechanisms and thresholds of ultrashort (down to femtosecond) laser systems. Currently, there is not safety standard for short pulses of 1 nanosecond and less. The ANSI laser standard working groups are supported.

A final area, medical diagnosis and treatment is a new mission area which will develop as a result of the Letterman Army Institute of Research collocating to Brooks AFB.

The CTAS-2 exercise was conducted at the AIRNET Warfighting Complex at Fort Rucker, AL. This simulation exercise examined the combat potential of laser weapons as an adjunct or stand alone air defense system in a force on force engagement. Information on opportunities of engagement (co-field-of-view) between aircraft and laser weapons was gathered. Glare, scotoma effects, and "eye defeat" were simulated and the reactions of aircrews with and without eye protection were recorded. Research is ongoing in our laboratory on many of the issues involved in this exercise.

Grating Acuity following Laser-Produced Central Retinal Lesions in Rhesus Monkeys and Simulated Lesions (Artificial Scotomas) in Human Subjects

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Retinal injuries from accidental laser exposure began to occur soon after lasers were introduced as a laboratory instrument. One of the earliest reported injuries was by Rathkey (1965). The number of such incidents has since continued to climb with the proliferation of laser technology. Aside from laboratory workers, one of the populations at greatest risk has been military personnel who work in operational environments where range finders and target designators are in use. In every documented case of laboratory and military laser retinal injury, there has been an associated disturbance of vision. In some cases, the effect was mild and quickly resolved (e.g., Case 2, Boldrey et al., 1981), but there has been an ample number of instances of profound loss of vision and only partial visual recovery (e.g., Henkes & Zuidema, 1975).

Tissue damage from ocular laser exposure can vary considerably, depending upon the parameter values of the laser. In a survey of laser accident cases, Wolfe (1986) divided tissue damage level into four categories. The lowest damage level, termed Grade I, was characterized by production of edema and slight tissue discoloration. In Grade II, the tissue was coagulated, producing a whitish appearance under ophthalmoscopic examination. Grades III and IV involved hemorrhages. The hemorrhage was contained within or beneath the retina in Grade III, whereas the blood spilled into the vitreal cavity in Grade IV. Damage level was further divided between injuries occurring within the retinal fovea (i.e., an area 5 deg of visual arc in diameter, centered on the foveola), or those occurring outside the fovea. To a first approximation, the visual deficit, as assessed by visual acuity, increased with injury grade, and was worse for foveal, as opposed to extrafoveal, damage. However, the extent of visual acuity loss varied significantly within a given damage level.

A limitation associated with accident case reports as a source of scientific information is the necessarily uncontrolled circumstances of the injury. That is, differences in the extent of the injuries, and when and how they were examined, make comparison across cases problematic. On the other hand, laboratory studies of laser injury have the advantage of control over the relevant parameters, insofar as they have been identified. Accident case reports may therefore function as a source of hypotheses to be tested in the laboratory.

Our laboratory has been interested in the quantitative study of the effect of Grade IV hemorrhagic lesions on visual acuity. Retinal injuries of this level represent a worst-case condition for performance of a task requiring spatial vision. Wolfe (1986) and others have shown that at this damage level, initial acuity may be quite poor (some accident victims have reported temporary, complete blindness in the injured eye), but a remarkable degree of recovery may also be achieved. Both the time course and extent of recovery can differ considerably across individual cases (e.g., Case 1, Manning et al., 1986 vs Lang et al., 1985). By studying this type of injury in the laboratory we hoped to learn more about the near-term effects as well as the time course of recovery. What will be reported here is progress of ongoing work.

HEMORRHAGIC LESION STUDIES

Two rhesus monkeys were used as subjects. The animals involved in this study were procured, maintained, and used in accordance with the Animal Welfare Act and the "Guide for the Care and Use of Laboratory Animals" prepared by the Institute of Laboratory Animal Resources - National Research Council. They were operantly trained with positive reinforcement to push a response lever when an acuity target was briefly (0.5 s) presented. The task was structured into a series of discrete trials, and one target was presented per trial. The target was a square-wave luminance grating at 90% contrast and 30 cd/m^2 space averaged luminance. Grating spatial frequency was varied in twelve steps from 0.4 to 26 cycles per degree (cpd). The stimulus field subtended 9.3 deg of visual angle at the viewing distance of 158.5 cm. When the grating was not present, the stimulus field was homogeneous and had the same average luminance as the grating.

Visual acuity was determined by a simple up-down psychophysical staircase procedure. Each correct response increased the spatial frequency by one step, whereas an incorrect response decreased spatial frequency by an equal amount. The staircase procedure increased the spatial frequency until the subject's resolution limit was reached; at that point, the spatial frequency tended to oscillate about the subject's detection threshold across trials. Each transition from detection to non-detection, or vice versa, marked an acuity estimate. Acuity was the mean of the two spatial frequencies associated with adjacent trials in which a correct response was given on one, and an incorrect response was given on the other.

Laser exposures were made by a Q-switched Nd:glass laser with a pulse duration of 20 ns and 1060-nm wavelength. One exposure was made per subject. The laser exposure took place while the subject was engaged in the visual acuity task. A dual Purkinje image (DPI) eye tracker, equipped with a device to stabilize the laser beam on the subject's retina (i.e., a Fundus Illumination and Measurement Instrument or FIMI), was used to guide the laser exposure onto the retinal target. Immediately after the exposure, the spatial frequency was set to the midrange level, and the staircase procedure was then used to follow the subject's acuity, just as it had in the pre-exposure baseline. At the end of the exposure session, the subject was anesthetized for fundus photography to document the retinal injury. The subject was able to resume testing on the following day.

ARTIFICIAL SCOTOMA STUDIES

Except in rare cases in which an eye is to be removed for medical reasons, experimental induction of laser retinal lesions cannot be performed in humans. Fortunately, there are means of safely simulating aspects of retinal lesions in human subjects. The voluntary informed consent of the subjects used in this study was obtained in accordance with AFR 169-3. Our laboratory has utilized a DPI eye tracker system to non-invasively produce visual field obscurations, which are likely to be one of the most salient features of severe retinal injury. These artificial scotomas were centered on the subject's fovea to simulate foveal centered lesions. Stabilization of the scotoma was maintained by the DPI eye tracker as the subject performed a visual acuity task.

Two visual acuity tasks were examined. One was grating detection, structured identically to that used for the rhesus monkey subjects. Due to apparatus constraints, the mean luminance level was at 5 cd/m^2 rather than 30 cd/m^2. The visual field was also slightly smaller (8 vs 9.3 deg), and the spatial frequency range slightly expanded (0.5 to 32 cpd vs. 0.4 to 26 cpd). A second acuity task, not used in the animal experiment, was identification of the gap in Landolt ring targets. Subjects moved a joystick to indicate the direction of the gap relative to the 12, 3, 6, and 9 o'clock positions. For both tasks, visual acuity was measured with an artificial scotoma present and with scotomas ranging from 1 to 6 deg of visual angle in size.

RESULTS

The data to be reported below reflect work in progress. No statistical analyses have been performed to verify that differences in acuity as a function of treatment conditions reach statistical significance at a selected level.

Visual acuity dropped to the lowest measurable levels (i.e., 0.4 cpd or 20/1500 Snellen) immediately after the laser exposure for both rhesus monkey subjects. After a period of 3 min in the case of subject 609Z and of 49 s for subject 454D, measurable recovery of visual acuity began. Subject 609Z reached an average acuity of 14.9 cpd (20/40 Snellen acuity) on the day of exposure (see Figure 1). The average acuity for subject 454D on exposure day was 8.5 cpd (20/71) (see Figure 2).

The acuity level for subject 609Z remained near 15 cpd for 13 days post-exposure, whereupon it rose to 21 cpd (20/29) and stayed close to this level until testing was completed 37 days post-exposure (see Figure 3). Average pre-exposure acuity was 22.7 cpd (20/26).

Acuity for subject 454D further declined during the first two post-exposure days to an average of 5.8 cpd (20/103), and then gradually improved to an average of 16.6 cpd (20/36) by post-exposure day 7 (see Figure 4). Average acuity remained close to 16 cpd until the completion of testing 37 days post-exposure. There was, however, a trend toward further improvement during post-exposure days 35-37 in which average acuity was between 17.3 and 18 cpd (20/35 - 20/33) (Fig. 4). Average pre-exposure acuity was 19.7 cpd (20/30).

Preliminary findings for grating acuity in the presence of artificial scotomas indicate acuity reductions comparable to those found with retinal lesions. For example, one subject showed an average acuity of 12 cpd (20/50) with a 6 deg scotoma and 19 cpd (20/32) with a 3 deg scotoma. These results bracket the grating acuity of both lesion subjects except during the early post-exposure period. Additional data on grating and Landolt acuity in the presence of artificial scotomas is anticipated.

ACKNOWLEDGEMENT

The research reported here was supported, in part, by Contract F33615-88-C-0631, let by the USAF Armstrong Laboratory, Occupational and Environmental Health Directorate, Directed Energy Division, Laser Branch, Brooks Air Force Base, TX.

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Figure 1

VISUAL ACUITY -- SUBJECT = 609Z

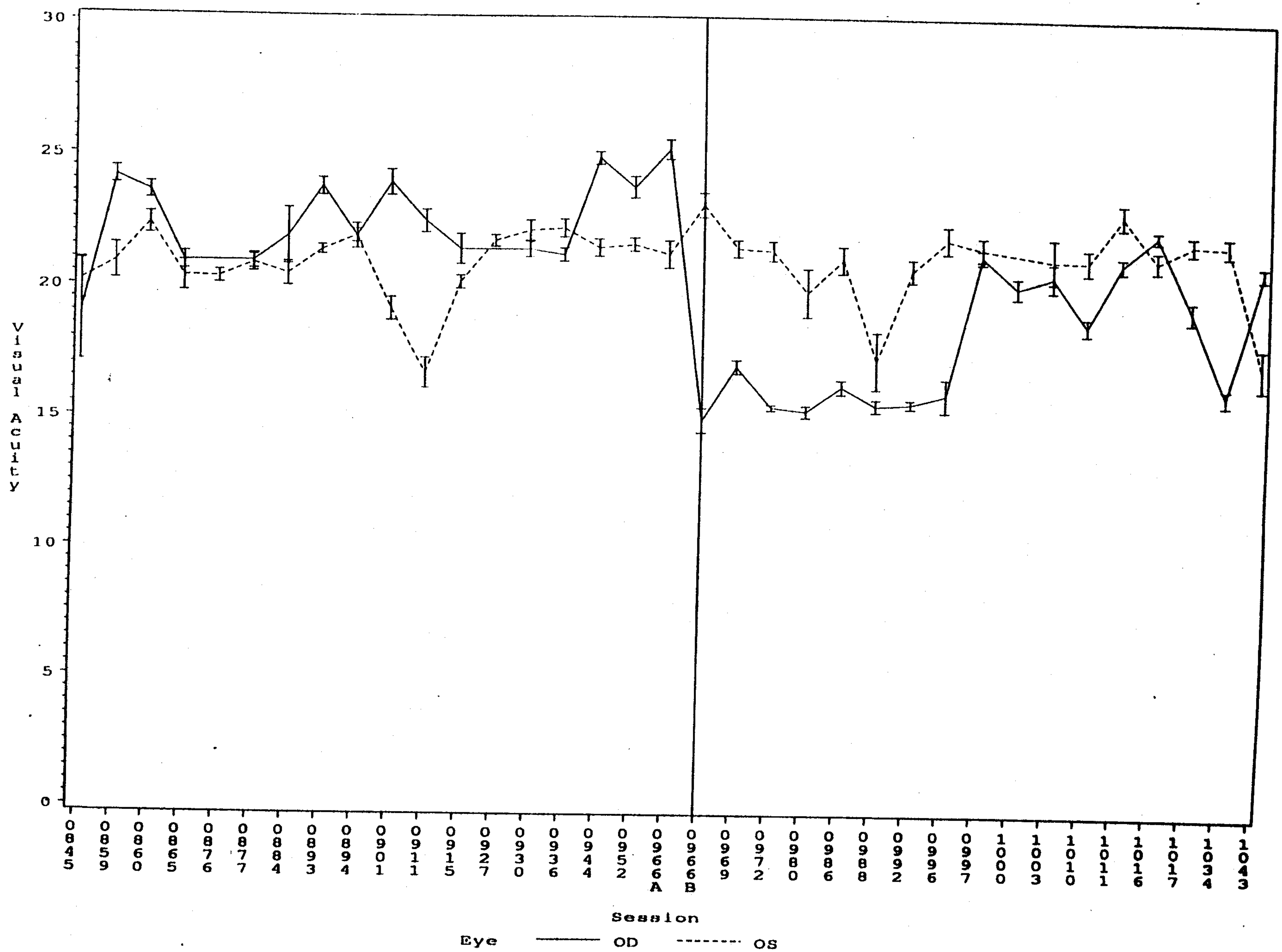


Figure 2

VISUAL ACUITY -- SUBJECT = 454D

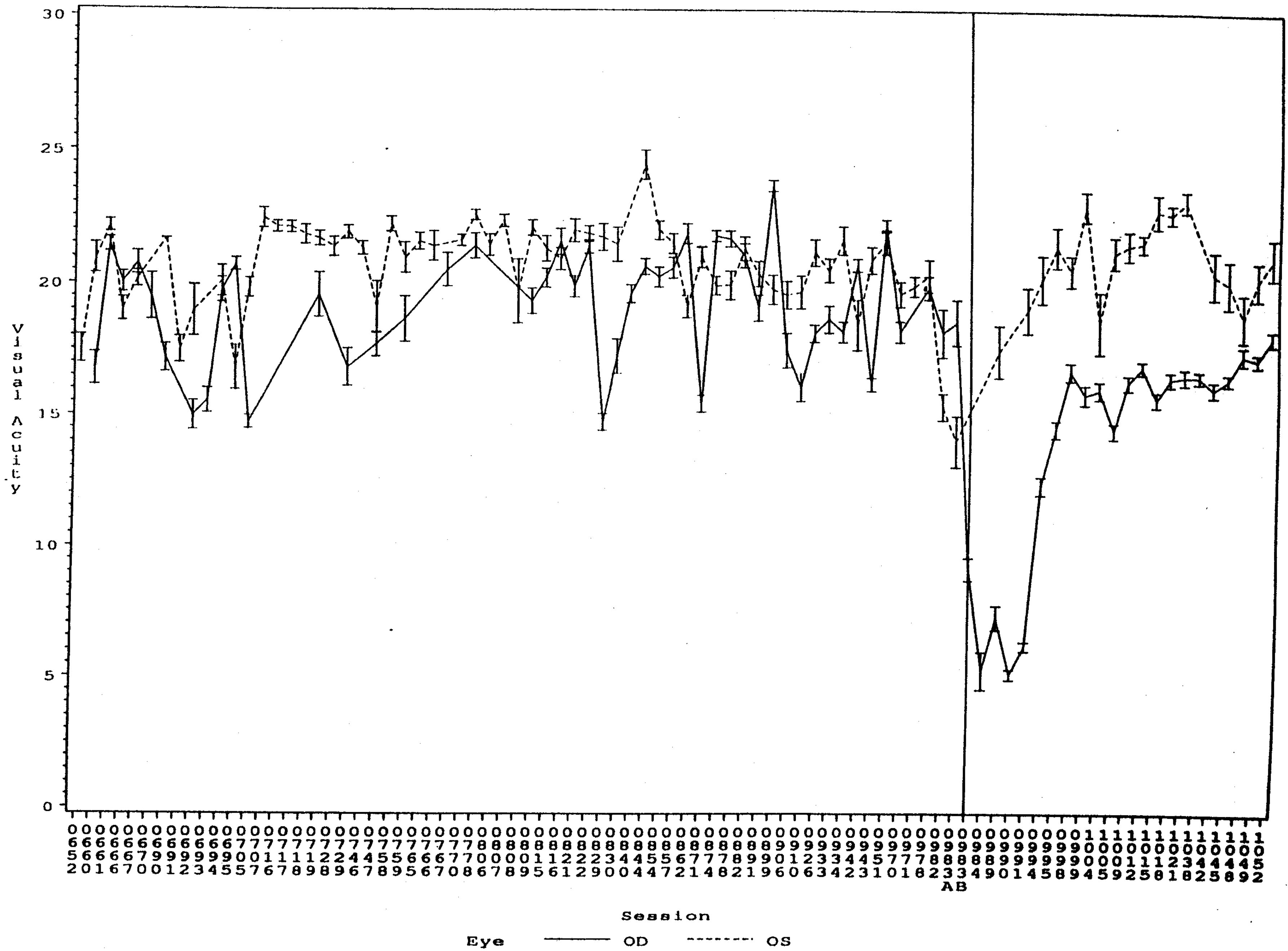
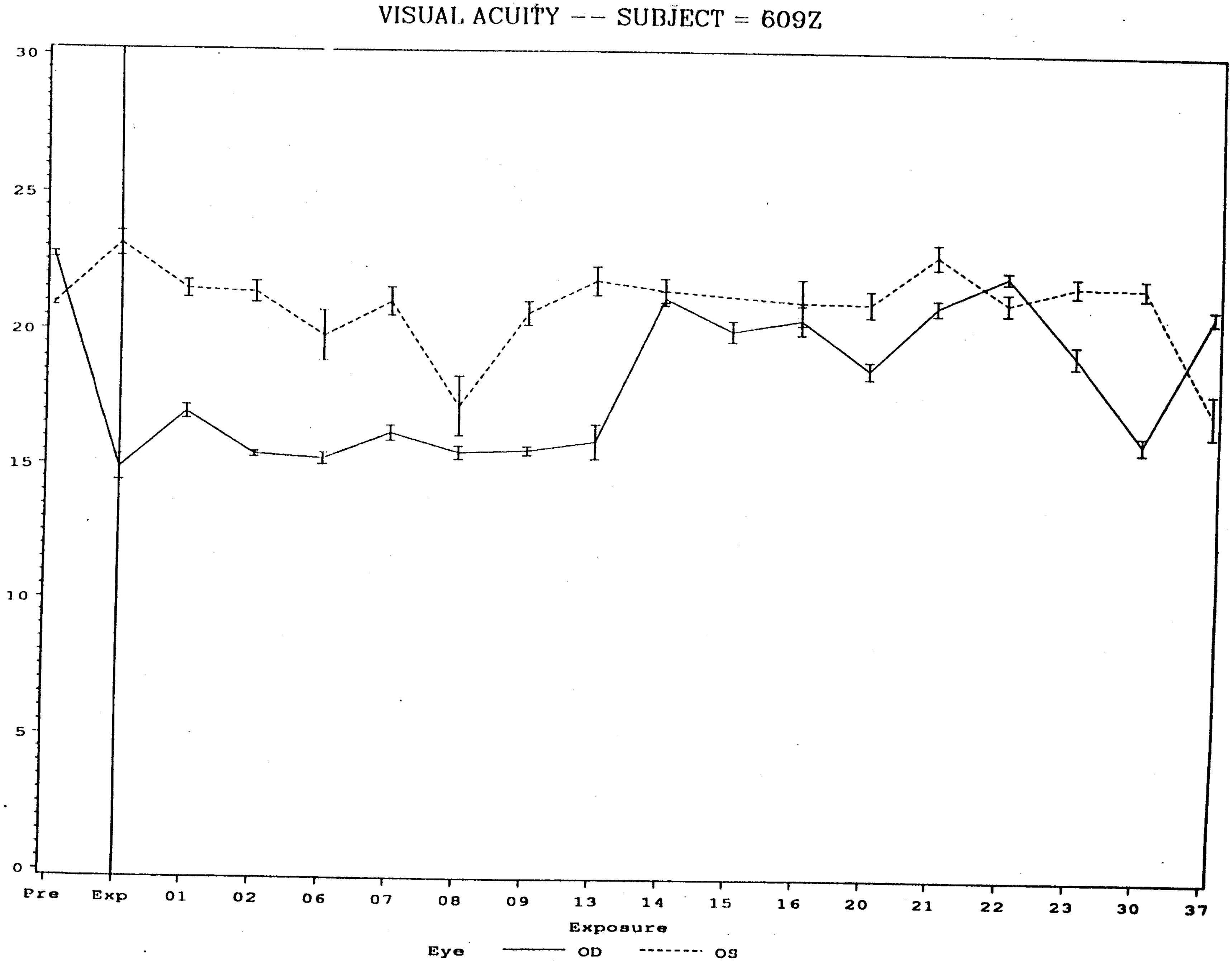


Figure 3



VISUAL ACUITY -- SUBJECT = 609Z
30
25
20
15
10
5
0
Visual Acuity
Pre
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01
02
06
07
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09
13
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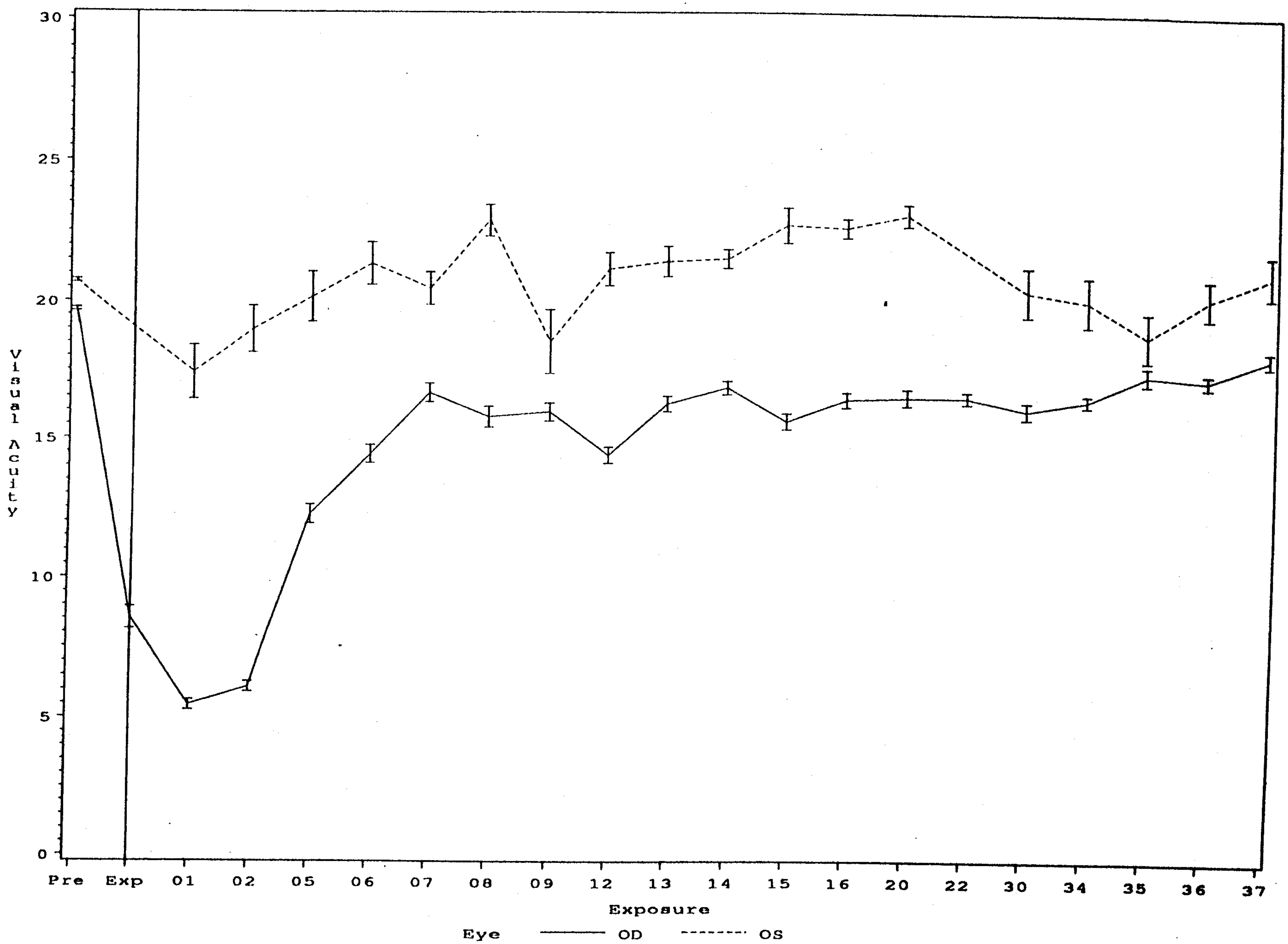
30
37
Exposure
Eye
OD
OS

Figure 4

VISUAL ACUITY -- SUBJECT = 454D



DOES WILSON'S HUMAN SPATIAL VISION MODEL HOLD FOR COMPLEX "REAL-WORLD" TARGET DETECTION?

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INTRODUCTION

Psychophysical and electrophysiological evidence suggests that human spatial vision is encoded by discrete neurophysiological channels which signal specific spatial frequency, orientation, and position information. Models of human spatial vision commonly consist of filters of various sizes which are located at different spatial locations and are selectively tuned to different spatial frequencies and orientations. Wilson's (1991) line element model was derived from human psychophysical data and consists of difference of Gaussian (DOG) filters tuned to 6 spatial frequencies and up to 12 orientations. These filters are weighted by the human spatial contrast sensitivity function, sampled at the Nyquist frequency of the human fovea, and pooled in accordance with nearest neighbor principles.

Previous reports suggest that only a small number of spatial-filtering channels, which are most sensitive to the target in question, signal at detection threshold (Campbell & Robson, 1968; Graham, 1989). Olzak and Thomas (1986) proposed that for a complex target (i.e., having multiple spatial frequencies or orientations), at a minimum, either a difference in the spatial frequency, orientation, or spatial location information should be required to produce threshold detection and discrimination. Theories and models of how the human visual system processes spatial information have been derived from psychophysical data which used relatively simple gratings (consisting of only one to three spatial frequencies with or without one to three orientations) as targets. Whether these models hold for data collected using complex, real-world targets is an open experimental question. Furthermore, the number of spatial-filtering channels (i.e., model filters) required for real-world, complex target detection has not been directly investigated.

EXPERIMENTAL GOALS AND RATIONALE

There are two primary goals for this project. The first goal is to determine if the Wilson (1991) model can be used to filter a complex target and adequately predict, from the relative magnitudes of the filters' responses, the spatial information required to detect a target of military significance at threshold. The second goal is to determine if the information from a very small number (i.e., 3 out of 16,000) of the Wilson model filters is adequate to signal threshold target detection. Our strategy was to determine if statistically equivalent detection thresholds could be obtained for a B-1 bomber target (Airplane target) and a second target produced from the visual outputs of three of the Wilson model filters with the highest response magnitudes after filtering the B-1 bomber target (Filter target).

Four experiments were performed to test our hypothesis. In Experiment 1, target contrast was systematically varied, which, theoretically, should minimize the number of activated spatial-filtering channels at threshold. In Experiments 2 and 3, static and dynamic Gaussian "white" noise was superimposed upon the targets at one of two fixed root-mean square (rms) levels, and target contrast was systematically varied to measure threshold. By definition, "white" noise should equally activate all spatial-filtering channels but only those most sensitive to the target should have enough signal strength to produce a detectable signal-to-noise ratio (SNR). The two noise rms levels should affect detection thresholds (i.e., higher noise rms levels should produce higher thresholds) but not the equivalence between the Airplane target and Filter target thresholds. Dynamic noise experiments can provide us with some insight as to the temporal characteristics of the filters used and their compatibility to ideal detector properties. Experiment 4 was designed to further validate the results of Experiment 1. Experiments 1 and 4 were identical except for the filters used to construct the Filter target. In Experiment 4, the Filter target was generated using the outputs of three filters (300-302) whose response magnitudes were one-half the amounts of the three greatest responding filters (1-3). If our theoretical assumption for Experiment 1 is correct, the Filter target used in Experiment 4 should produce detection thresholds which are significantly different (and higher) than those measured for the Airplane target.

MATERIALS AND METHODS

Subjects:

Six observers (male and female), ranging in age from 28-41 years, served as subjects in each of these experiments. The voluntary informed consent of the subjects used in this research was obtained in accordance with AFR 169-3. The subject population for Experiment 4 differed slightly from that of the other experiments. All subjects had visual acuities correctable to 20/20, normal fundus examinations, and normal color vision.

Target and Noise Production:

The DOG filters of Wilson's (1991) model were programmed on an image-processing system (IPS) consisting of a microVAX computer with a Parallax framebuffer and PV~WAVE software (Precision Visuals). Approximately 16,000 filters were installed to represent the six different filter types sampling a 0.5° X 0.5° area of the foveola at the Nyquist frequency (Williams, 1985). A photograph of a B-1 bomber was digitized on the IPS and displayed on a color CRT monitor as a 0.4° X 1.39° target on a 6.73° X 8.68° photopic (50 cd/m^2) "white" (x = 0.28, y = 0.32) background. The Airplane target was then filtered using the Wilson model, and the magnitude of the filters' responses was plotted and analyzed. The absolute values of the filters' response magnitudes were then calculated and analyzed to determine which filters had the greatest response magnitude. The three filters with the highest response magnitude (or the three with one-half of the greatest response magnitude) were recombined to produce the second Filter target(s).

Gaussian noise used in Experiments 2 and 3 was generated using PV~WAVE and displayed as a 256 X 256 inset (128 X 128 image zoomed by a factor of 2). This 1.59° X 1.79° inset was superimposed upon the targets at either 15 or 35 rms. Noise mean luminance was always 50 cd/m^2. Dynamic noise differed from static noise in that the pixel values were varied as a Gaussian function over subsequent frames as well as across the noise inset. Dynamic noise integration frequency was 30 Hz and noise patterns were randomly generated for each subject testing session (i.e., experimental run).

Procedure:

A two-alternative forced choice procedure was used for all experiments. Following 3 min of light adaptation to the background, an adaptive staircase procedure (Harvey's (1986) ML-TEST procedure) presented the targets randomly at different contrast values. The subject's task was to determine in which of two sub-trials a target (either target) appeared. Six staircases (3 per target type) were run within an experimental session and three experimental sessions were performed by each of the six subjects. ML-TEST ended the experiment when a 95% confidence interval had been obtained about each staircase's threshold. Thresholds corresponded to the Weber contrast (Experiments 1 and 4) or luminance-based rms (Experiments 2 and 3) to which a 82% correct response was obtained.

Analysis of variance statistical tests were performed to determine the effects of the main factors of target type, subject, experimental session, and their interactions (independent variables) on detection thresholds (dependent variable). For Experiment 4, the main factor of experimental session was not analyzed.

RESULTS

Results from Experiments 1 and 2 indicate the Airplane and Filter (filters 1-3) targets yield statistically equivalent detection thresholds. None of the three main factors had a significant influence on detection thresholds under contrast reduction or static noise superimposition. This finding was true for both noise rms levels used in Experiment 2. Results from Experiment 3 indicate the two targets yield statistically different thresholds using both noise rms levels. The main factor of target type was found to significantly influence the detection thresholds ($p < 0.05$). Post-hoc sign test analysis indicated that Airplane target thresholds were significantly larger than Filter target thresholds ($p < 0.05$) for both dynamic noise rms levels. These data indicate that the 30 Hz temporal integration of the noise enhanced Filter target detection more so than Airplane target detection. Furthermore, post-hoc analysis indicated that although always lower, dynamic noise thresholds could not be predicted from static noise thresholds using the ideal detector theory (dynamic noise thresholds = static noise thresholds X 1/sq. root of 30). Results from Experiment 4 indicate that the Airplane target and the Filter target (filters 300-302) also produced significantly different thresholds. The main factor of target type had a significant effect on detection thresholds ($p < 0.05$). For all but one subject, Filter target thresholds were higher than Airplane target thresholds.

DISCUSSION AND CONCLUSIONS

Our data indicate that the Wilson (1991) model can be used to predict the spatial information (spatial frequency, orientation, spatial location) required to detect static complex targets on static backgrounds. For static targets, it appears that the spatial information from a very small number of filters with the highest response magnitudes to the Airplane image is sufficient to signal threshold detection. Introducing temporal characteristics to the background removes the model's prediction capability under our experimental conditions. This result does not surprise us because the Wilson (1991) model is a <u>spatial</u> vision model not a <u>spatiotemporal</u> vision model. However, the extracted spatial information contained within the Filter target appears to be easier to detect at threshold under dynamic background conditions than is the actual Airplane target. Further experimentation is required to determine the applicability of using the model to enhance target detection on dynamic backgrounds. We also do not know whether target discrimination is enhanced by this type of target compression. However, use of the Wilson (1991) model for applications in static scenes or environments with little to no significant temporal characteristics is very encouraging.

We have several lines of investigation to pursue to continue to verify and expand upon the Wilson model. We are currently testing the model using a similar paradigm as that described above to determine if our results are true for static target discrimination as well as detection. Experiments to determine whether similar flashblindness recovery times can be obtained for the Airplane and Filter targets have also been planned. In addition, we would like to experimentally determine the temporal bandwidths of the different

spatial frequency-tuned filter types in attempt to expand the model's applications into the spatiotemporal domain.

ACKNOWLEDGEMENTS

We thank Dianne Mirro, Marta Myers, Mary Headley, and Vickeylynne Morrow for their excellent technical assistance on this project. We also gratefully acknowledge Dr. Denise Varner for her many helpful discussions on the design and concepts for several of these experiments. This work was supported by contract #F33615-88-C-0631, let by USAF Armstrong Laboratory, Brooks AFB, Texas, to KRUG Life Sciences Inc., and by an Independent Laboratory Investigative Research Award to Capt Norm Barsalou by the Armstrong Laboratory.

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Target Acquisition Simulation using Real-world Targets and Backgrounds

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INTRODUCTION

Visual target acquisition is a critical component of air-to-air engagements. Loss of visual contact with the adversary, even for a few seconds, can seriously jeopardize the safety of the aircrew. Lasers have the capability to cause transient or prolonged disruption of visual processing. The purpose of this study was to estimate the effects of temporary visual loss from a laser exposure on target acquisition performance.

The target acquisition task involves detecting a target within the search scene. Often, a target must be detected against a natural background that may have a complex luminance distribution. In cases in which the background is sufficiently complex to impose significant structure or distractors on the search scene, the task changes from detection to the more difficult task of recognition. Thus, background features will have a significant influence on target acquisition performance.

Another goal of this project was to evaluate the effect of target contrast and scene complexity on acquisition performance. This goal presents a technical challenge because target parameters must be held constant from background to background. While this requirement is not difficult to achieve for parameters such as size, shape, and orientation, controlling contrast is difficult because target contrast is intimately linked to the background on which it appears. The problem we faced was how to control target contrast in the presence of variable backgrounds.

We developed a technique that maintains target contrast at a constant level despite a changing background. Our approach capitalized on a common method for defining the luminance variation in a scene, the root-mean square (RMS) contrast. The technique involves varying the target luminance to achieve the desired contrast, while leaving the local background intact. By varying only the target luminance, contrast can be controlled independently of the background.

Because our technique controls contrast on virtually any background, we were able to directly compare search performance for the same target on different backgrounds. At issue was whether search data for targets on uniform backgrounds (detection) are predictive of performance for the same targets on other, more complex backgrounds (recognition).

We used three qualitatively different backgrounds to globally assess the effects of background complexity on visual search. The backgrounds were a structureless, uniform background, a natural terrain background, and a similar natural terrain in motion. This last background was video footage of natural terrain shot from a low-flying aircraft. In addition, target contrast was varied within each background. The effects of laser exposure, background complexity, and target contrast on target acquisition performance were studied.

METHOD

Twenty-four male subjects participated in the experiment, eight in each background condition. Subjects had normal vision as tested by a complete ophthalmological exam. All subjects were naive about the nature of the task. The voluntary, fully informed consent of the subjects used in this research was obtained as required by AFR 169-3.

The target was an aircraft silhouette of uniform luminance subtending 0.6° of visual angle. Target contrast was computed as the RMS of the aircraft plus the local background area. The luminance of the aircraft was adjusted to achieve contrasts of .15, .25, .35, and .45 RMS.

Figure 1 shows how target contrast varies with the luminance of the target. It has a kind of "V" shape. At very low target luminance values, the contrast is high; when the target luminance equals the mean luminance of the background, contrast reaches a minimum. Then, target contrast increases again as the target luminance exceeds the mean luminance of the background.

Figure 2 shows the natural terrain background. Figure 3 illustrates enlarged views of the target at the four test contrasts.

The same procedure was followed for computing target contrast for the uniform and the dynamic backgrounds. The contrast algorithm was simply repeated for every frame of the video sequence. Target and background images were processed with Precision Visuals PV-WAVE software.

A trial began with the observer monocularly fixating the center of a monitor placed 66 cm away. It provided a 23° X 23° field of view. The background image then appeared with the target positioned in a random location. The observer searched the image and pressed a button when he found the target. His search time was recorded, and a set of 12 boxes appeared on the image, in random locations. One of the boxes was in the same location as the target. The observer picked one of the boxes, and his response was recorded as right or wrong.

Trials with uniform and terrain backgrounds had time limits of 90 s. The limit for the dynamic background condition was 30 s. If the subject did not find the target within the allotted time, the trial was terminated and response time was scored as 90 or 30 s, respectively.

On trials in which a laser exposure occurred, the 100-ms flash was coincident with the image onset. The flash was superimposed on the image by a beamsplitting pellicle. It was seen in Maxwellian view and was 10° in diameter. The 514-nm light flash was generated from a Spectra-Physics 168B

argon laser. Flash energy was 1.47 mJ which corresponded to a retinal illuminance of 7.4 log td-s.

One experimental session consisted of 12 flash and 12 no-flash trials, presented in random order. The four contrast levels were also randomly presented within a session, but were equally distributed across the flash and no-flash trials. A total of 96 trials was collected on each observer.

The data were analyzed in a Background (3) X Contrast (4) X Flash (2) X Zone (3) mixed factorial design. The Background variable was a between-groups factor and all other variables were repeated factors. We transformed the data into logarithms to normalize the search-time distributions.

RESULTS

The ANOVA revealed two significant three-way interactions. The Background X Contrast X Flash interaction was significant $F(6,63) = 18.76$, $p < 0.0001$, and the Background X Contrast X Zone effect, $F(12,126) = 2.45$, $p < 0.01$, was also significant.

The first interaction is shown in Figure 4. As expected, the laser flash caused an elevation in search time. The increase in search time was anywhere between 4-10 times the baseline level. Furthermore, regardless of the flash condition, search times were longest for the natural terrain background, followed by the dynamic, and the uniform backgrounds. However, the amount search time was elevated depended on the type of background and target contrast. In general, the laser flash had a greater effect as contrast decreased and for the natural terrain background. The case in which this rule did not apply was for the natural terrain background at the 0.15 RMS contrast. However, this was due to a ceiling effect caused by the time limit imposed on the search times.

The second interaction involving Background, Contrast, and Zone is shown in Figure 5. This effect was similar to the 3-way interaction cited earlier, in that search time increased as contrast decreased and as background changed from uniform to dynamic to natural terrain. However, the order of these effects depended on the zone in which the target was located. The largest effect was seen at the 0.15 RMS contrast. No differences between zones were found in the uniform background condition. However, an advantage for targets located in the inner zone was observed in the dynamic background, and a disadvantage was seen for the outer zone. The opposite was true for the natural terrain background. Here, shorter search times were found for the outer zone, and longer times were observed for the inner zone.

Another significant effect was found in the Zone X Flash interaction, $F(2,42) = 8.41$, $p < 0.001$. This interaction, shown in Figure 6, demonstrated that search times were shorter as the target moved from the outer to inner zones of the search field in the baseline condition. However, this advantage disappeared in the flash condition where a slight elevation in search time was observed for targets in the inner zone.

We also examined the distributions of search times for various conditions. Upon examination of these distributions, it became clear that a considerable amount of variability surrounded some of the conditions but not others. For

example, variability in search time increased substantially with decreasing contrast in the natural terrain condition. To illustrate this point, Figure 7 depicts two response distributions of the baseline data of the natural terrain condition: the 0.15 and the 0.45 RMS contrasts. These distributions show widely scattered search times in the case of the 0.15 RMS value and a narrow distribution of responses for the 0.45 RMS condition. The difference in these two distributions represents a fundamental difference in search behavior. The nature of this difference is explored in the discussion.

DISCUSSION

It is clear from these results that search behavior varied depending on the type of background the target was searched against, even though the target itself did not change. It is interesting to note the facilitating effect motion had on target detectability. Even though the target appeared on a terrain background similar to the static natural background, search times were considerably shorter. The moving background served to separate the target from other features in the background that could either camouflage the target or serve as distractors.

The results also revealed that no simple relationship existed between the search times of the various backgrounds. For example, one could not simply apply a multiplier to the mean search times of the uniform background to arrive at the mean search times of the dynamic or natural terrain background conditions. There has been some suggestion that a simple linear scaler could be applied to go from detection to recognition (van Meeteren, 1990). However, this does not seem to be the case for visual search. When going from detection to recognition, as evidenced by the transition from the uniform to the natural terrain background, the change in search time depended on target contrast and which background it was seen against.

The large variability in search time distributions between the high- and low-contrast levels suggested that more than one factor was dictating search performance. The results indicated that contrast alone was sufficient to drive search performance at high-contrast levels, but not at low-contrast levels. At low contrast levels, recognition decisions may be based on target shape, edges, or other features.

Finally, the effect of the flash was to increase search times. Search times were not uniformly increased but varied three- to tenfold depending on target contrast, background complexity, and location in the search field. These effects can be explained if one takes into account that only the central 10° of the retina was flashed and that the sensitivity of the peripheral retina remained unaffected. Furthermore, the rate at which each retinal location recovered from the flash depended not only on the flash parameters but also on the sensitivity of a particular retinal location to the target.

ACKNOWLEDGEMENTS

Thanks go to the many people that worked on this project including Anthony Catalano, James Brakefield, Gary Noojin, David Stolarski, Rowe Elliott, and the Analysis Branch of the Directed Energy Division (AL/OEDA). This research was supported by the USAF Armstrong Laboratory, Occupational and Environmental Health Directorate, Directed Energy Division, Laser Branch, Contract F33615-88-C-0631 to KRUG Life Sciences Inc.

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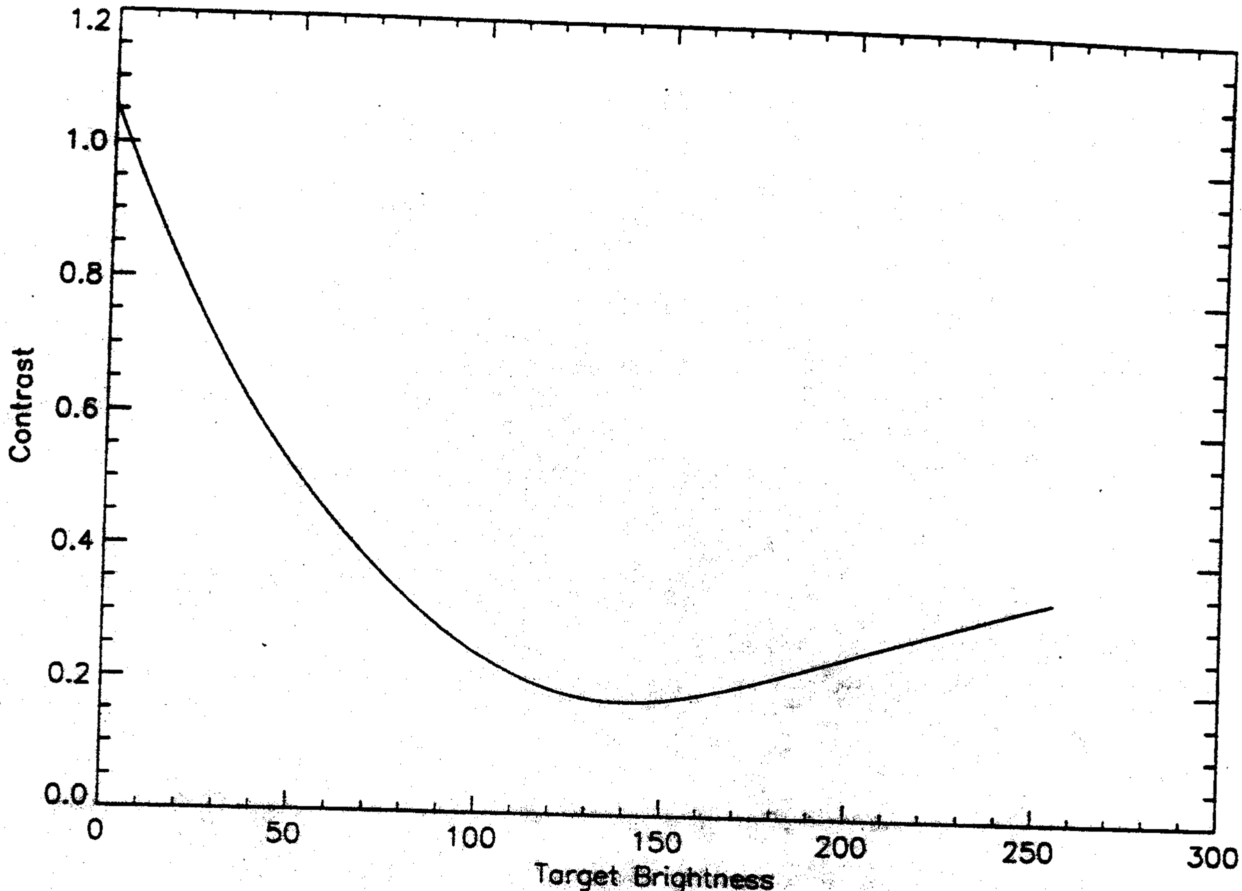


Figure 1. A graph of target contrast as a function of target luminance.

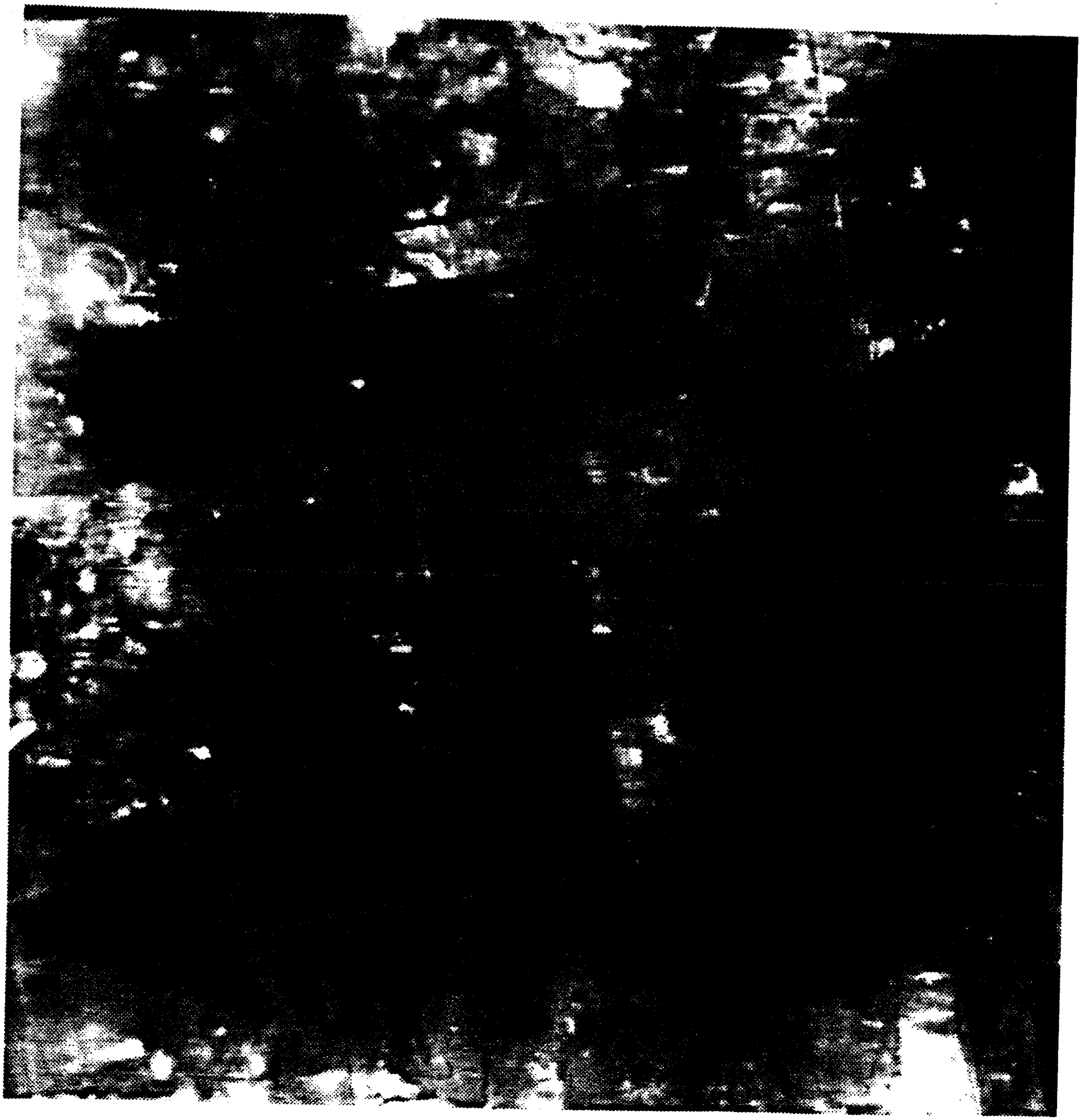
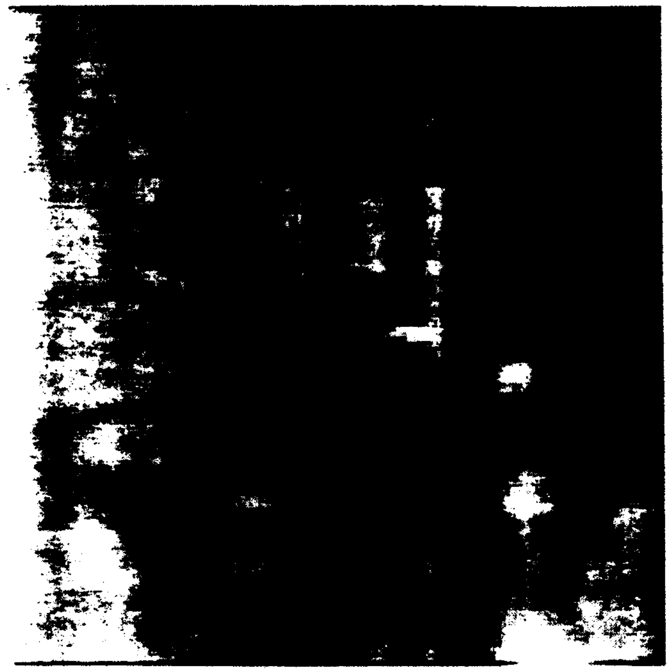


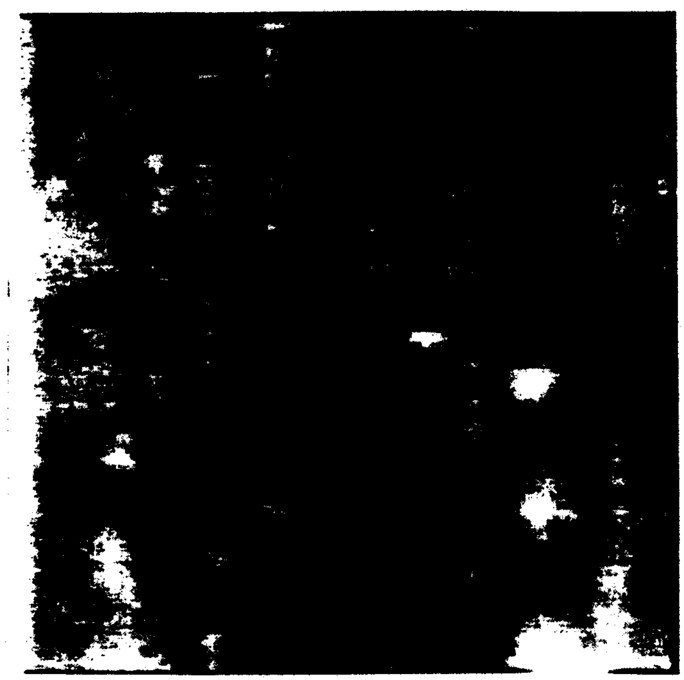
Figure 2. Photograph of the natural terrain background.

.45 RMS



.35 RMS

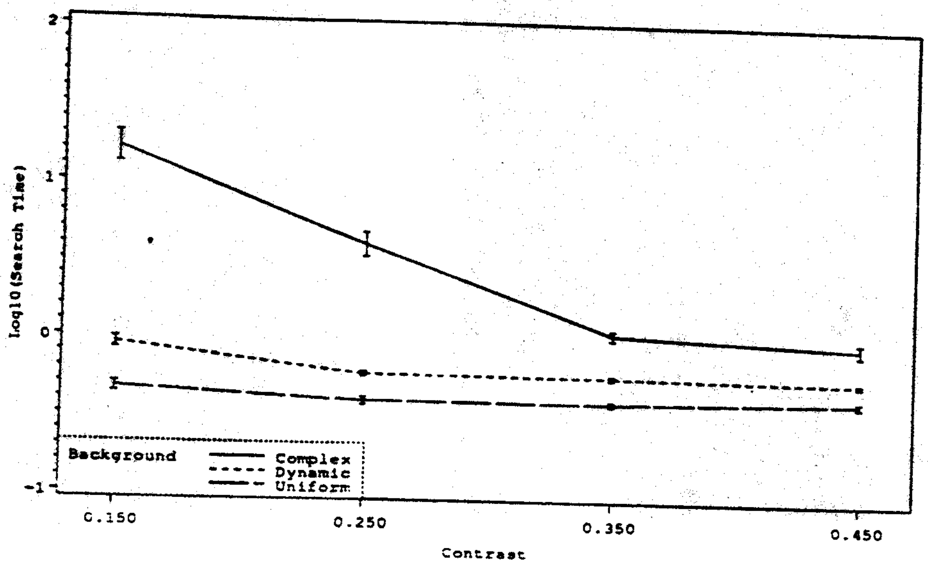
.25 RMS



.15 RMS

Figure 3. The test target at four contrasts.

No Flash



Flash

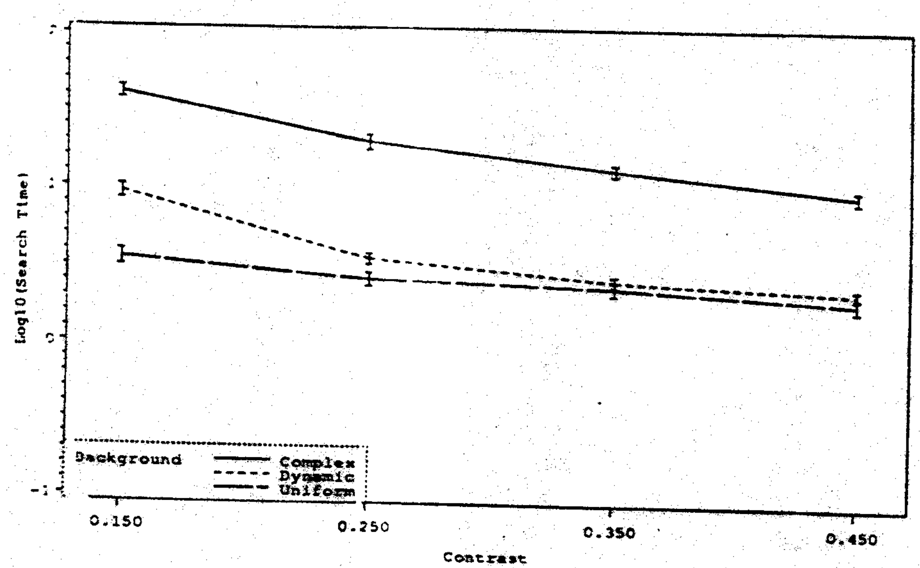


Figure 4. The Background by Contrast by Flash interaction.

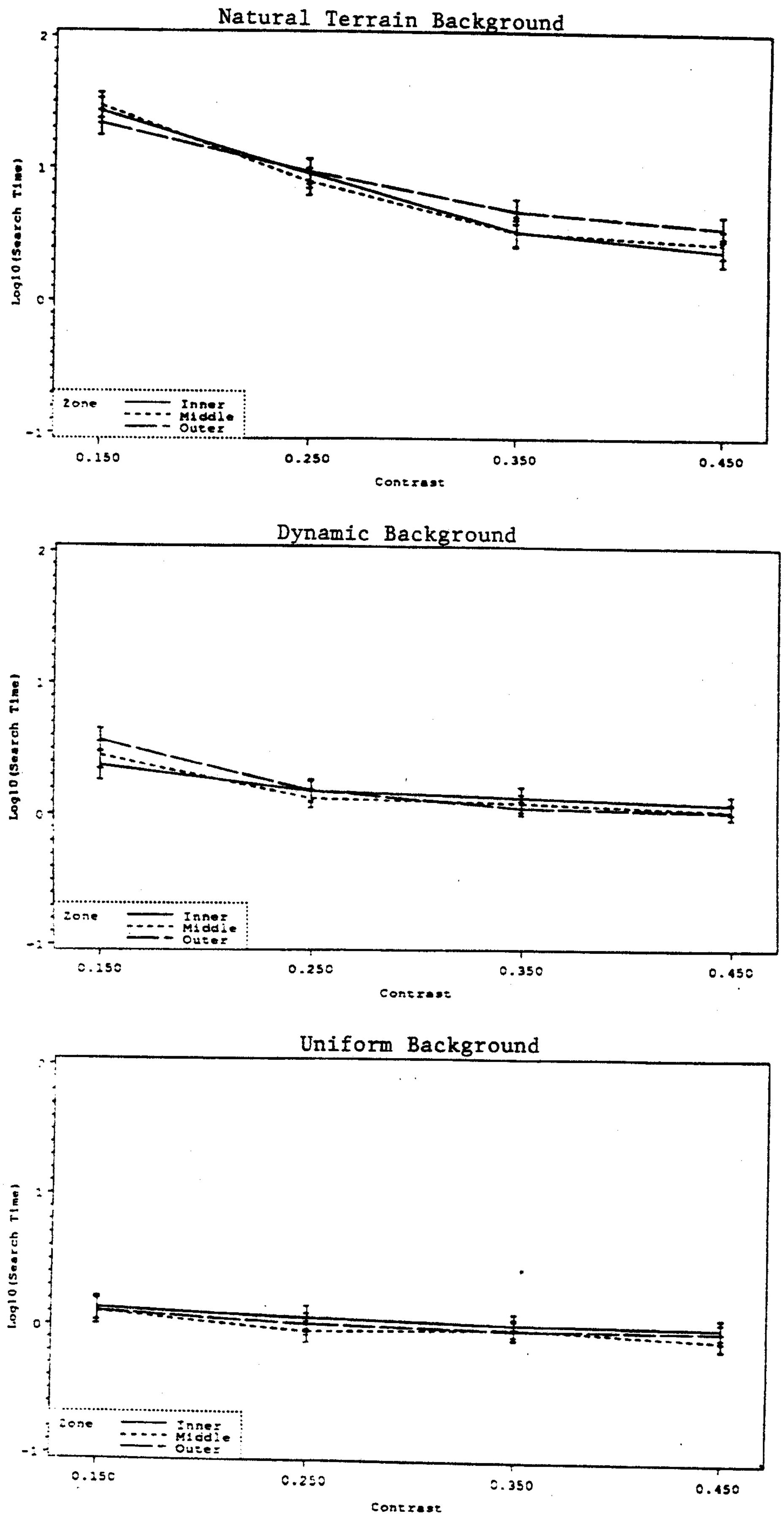


Figure 5. The Background by Contrast by Zone interaction.

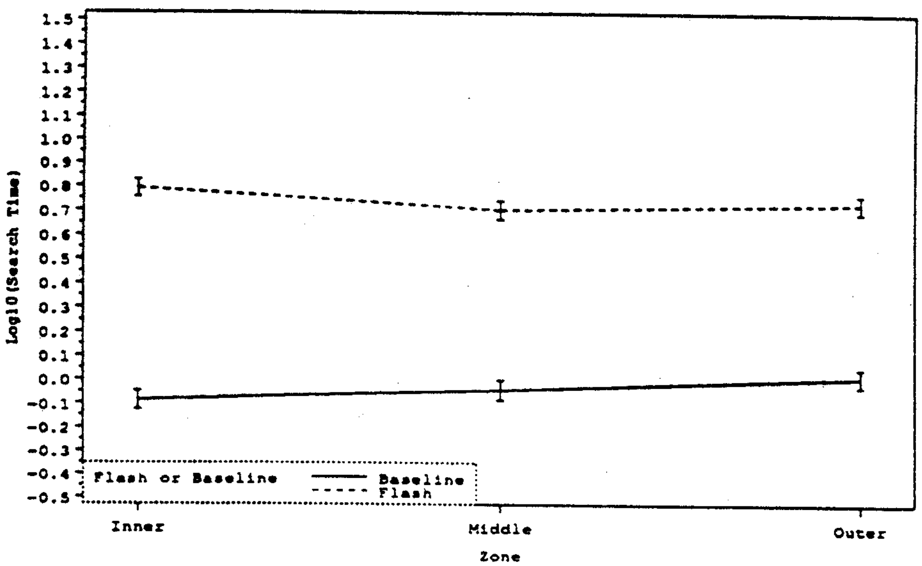


Figure 6. The Zone by Flash interaction.

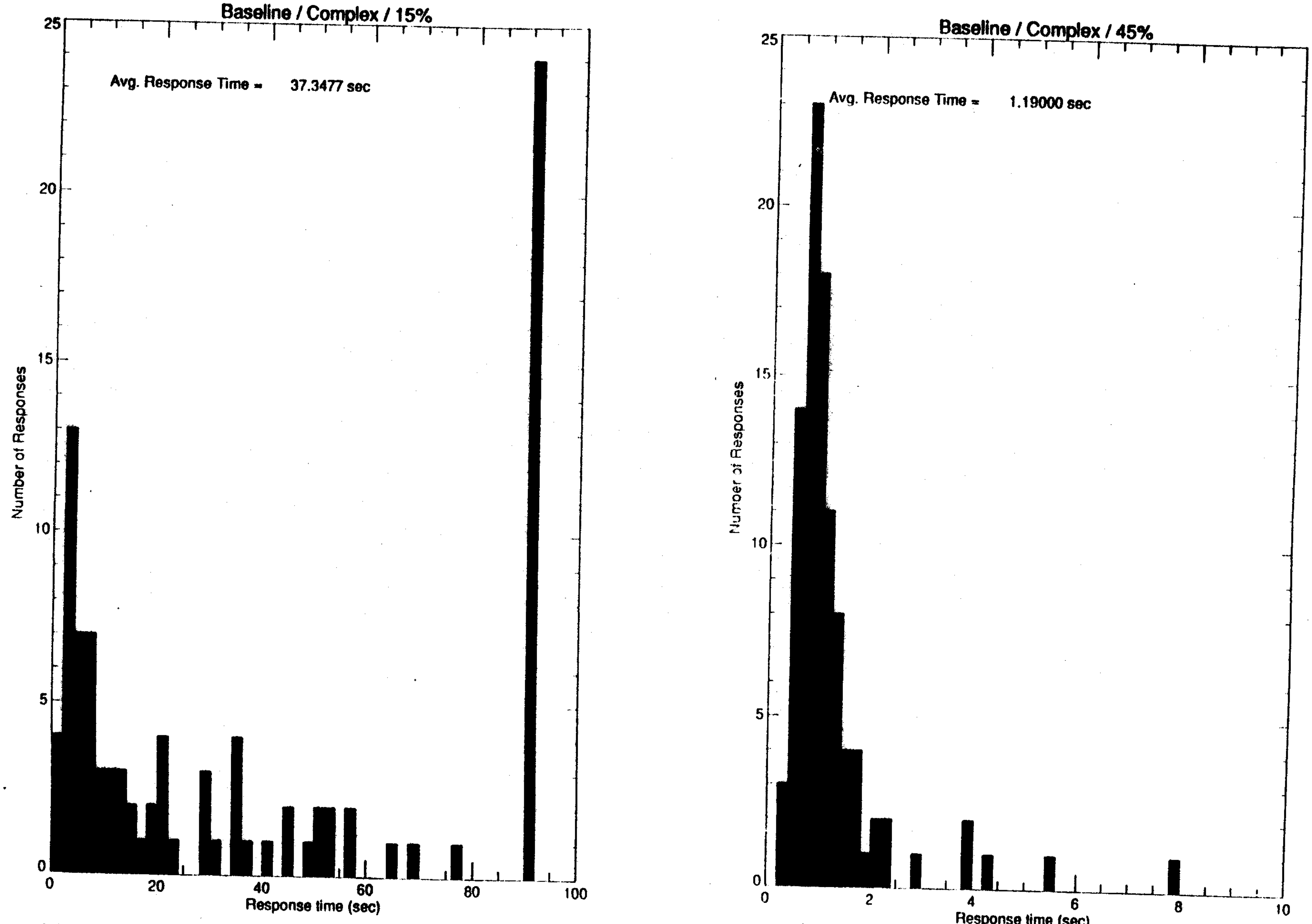


Figure 7.. The frequency distributions of the 0.15 and 0.45 RMS contrast targets for the no-flash, natural terrain background condition.

TARGET IDENTIFICATION REQUIREMENTS IN TACTICAL SIMULATORS

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David C. Hubbard, University of Dayton Research Institute

Out-of-the-cockpit visual cues are required for many of the tasks pilots perform in normal flight operations, as well as air-to-air combat and surface attack missions. For this reason, flight simulator visual systems must be capable of displaying the visual cues pilots normally use at the distances that are encountered in actual flight conditions to provide an effective training medium for these tasks. In air-to-air combat sorties performed within visual range, the pilot must visually distinguish the target aircraft up to distances of three nautical miles; in surface attack missions, the pilot must visually identify a prescribed target from an array of objects on the ground; and in landing approaches, pilots must visually monitor the terrain surface to maintain the proper altitude and course on the descending approach.

A wide range of visual system design variables can influence the visibility of cues in a simulated visual scene, however, hence the specific values of these variables will dictate the training effectiveness of the simulation. A decade ago (Statler, 1981), a seminal paper was produced entitled "Characteristics of Flight Simulator Visual Systems," in which critical design parameter were identified and defined. The paper addressed the three major properties of visual systems: spatial, energy, and temporal properties. The spatial parameters included field-of-view size and shape, viewing region of the observer, viewing distance, image mapping, and scene content; the energy properties included color, contrast, luminance, and resolution; and the temporal factors included scene excursion limits, transport delay, noise, refresh rate, and aliasing.

Research is currently being conducted at the Aircrew Training Research Division of the Armstrong Laboratory to establish the visual display requirements for various simulated flight tasks. In one investigation, the visual cues pilots use in air combat engagements to determine the orientation of the target aircraft were investigated. Additionally, a two-phase evaluation was accomplished addressing the field of view and resolution required for area-of-interest (AOI) displays. The specific objectives and research methods corresponding to these research efforts are described below, along with the progress to date.

Visual Cue Requirements for Air Combat Simulation

In air-to-air combat engagements that are performed within visual range, pilots fly their aircraft at or near the limits of the performance envelope with little or no reference to inside instruments. The pilots must constantly monitor the aspect angle

and range of the target aircraft, which dictate the offensive or defensive maneuvers the pilot employs. Due to the intense visual demands imposed upon the pilots, the effectiveness of a flight simulator for air combat training will be highly influenced by the display characteristics of the visual simulation system. Several of the most critical display characteristics are contrast, brightness, and resolution, which mediate the simulated distances the target stimuli are visible in the visual scene. Ideally, the visual system should provide the visual cues pilots normally use at the simulated distances corresponding to real-world operations. In order to determine the minimum requirements for each of the relevant display characteristics for the purpose of providing realistic training, the visual cues pilots use and the distances they are acquired must first be established.

The objectives of this investigation were: (1) to determine how accurately pilots can recognize the aspect angle of target aircraft images at various distances, (2) to identify the visual cues pilots use to establish the target aspect angles, and (3) to examine the influence of different aircraft pitch and bank angles on aspect angle recognition errors.

The visual stimuli were photographic slide images of 1/48-scale F-15 and F-16 fighter aircraft models. The pilots' task was to identify the aspect angle, direction of travel, pitch angle, and bank angle of the aircraft and to indicate the visual cues (aircraft features) they used. Each pilot viewed a total of 16 practice slides and 64 test slides. The test slides consisted of 16 different aircraft orientations (aspect angle, direction of travel, pitch, and bank combinations) at four simulated distances (.5, 1, 2, and 3 nautical miles). Four groups of pilots served as observers (instructor pilots, C/TX students, B-Course students, and operational pilots), and 20 pilots were used in each group. One half of the pilots in each group viewed the F-15 aircraft slides; the other half were administered the F-16 aircraft slides. The data were collected on-site at Hill AFB, UT; Holloman AFB, NM; Luke AFB, AZ; and the Arizona Air National Guard, Tucson, AZ.

Data collection has been completed. The data are currently being analyzed and a final report is being drafted to document the results of the investigation.

Area-of-Interest (AOI) Display Requirements for Low-Altitude Flight Simulation Tasks

Area-of-interest (AOI) displays for flight simulator visual systems were developed in response to a requirement for higher display resolution and image detail. AOI displays consist of a movable, high-resolution inset that is surrounded by a lower resolution, wide-angle peripheral field, and the AOI may be head tracked, eye tracked, or simultaneously head and eye tracked. Two of the most critical visual characteristics associated with AOI visual systems are AOI field of view (FOV) and resolution.

Research conducted to date (Turner, 1984) indicates that the AOI FOV and resolution requirements are task specific. Consequently, a research program comprised of a progressive series of display evaluations was initiated at the Aircrew Training Research Division addressing the effects of AOI FOV and resolution tradeoffs on observer performance in simulated low-altitude flight. Two investigations in the study series were conducted and a third is in the planning stage.

The Limited Field-of-View Dome (LFOVD) visual simulation system was used in the two investigations that have been completed. The LFOVD provides two optional AOI displays: a small, higher resolution AOI and a large, lower resolution AOI. The FOV size of the small AOI was 26.44 degrees horizontal by 20.51 degrees vertical, and the resolution (defined as the width of the line spread function at 50 percent of the line's maximum luminance) was 0.081 degrees horizontal and 0.071 degrees vertical. The FOV size of the large AOI was 40 degrees horizontal and 30 degrees vertical, and the resolution was 0.132 degrees horizontal and 0.121 vertical. An optical blend region was installed between the AOI inset and the surrounding visual field to provide a smooth transition between the two areas, and the blend regions of the small and large AOI sizes were 2.5 and 5 degrees, respectively. The instantaneous FOV, which is specified by the maximum dimensions of the surrounding visual field, was 60 degrees vertical by 140 degrees horizontal. The AOI was head tracked and could be rotated up to 90 degrees left and right, 40 degrees upward, and 22 degrees downward from a point directly in front of the cockpit at eye level.

The objectives of the first investigation were: (1) to determine the detection threshold distances for simulated ground targets in the small and large AOI displays and (2) to examine the effects of various stimulus characteristics on the detection thresholds. The stimuli were cylinder-shaped objects that were placed upright on the terrain surface of the visual database, and both striped and plain cylinders were used. The striped cylinders were modeled with a black stripe that encircled the cylinders and that were placed midway between the top and bottom of the cylinders. The plain cylinders were modeled without the stripes. Nine different cylinder sizes were used, which were produced by combining three cylinder heights (50, 75, and 100 feet) and three cylinder diameters (25, 50, and 75 feet). Additionally, two stripe sizes were used with each of the cylinder sizes: a 4-foot and an 8-foot stripe. The stimuli were presented in the center of the AOI displays, and threshold detection distances were obtained for both the cylinder stripes and the plain cylinders. For the cylinder stripes, the observers moved the simulated aircraft backward until the stripes disappeared and then forward until the stripes reappeared. For the plain cylinders, the observers moved the aircraft until the entire cylinder disappeared and reappeared.

The analysis of the thresholds associated with the cylinder stripes indicated that: (1) the detection distances were about 50 percent greater on the average with the higher resolution AOI than

with the lower resolution AOI; (2) the distances were slightly greater for the 8-foot-high cylinder stripes than for the 4-foot-high stripes; (3) the detection distances for the stripes increased as the height of the cylinders increased, and the percentage improvement in detection distance was greater between the shortest and intermediate cylinder heights than between the intermediate and tallest heights used; and (4) the distances increased as the diameter increased, and the percentage improvement in detection distance was greater between the narrowest and intermediate cylinder diameters than between the intermediate and widest diameters employed. The detection thresholds for most of the plain cylinders were governed by the settings used for the various image generator parameters. Only the smallest cylinder diameters were not influenced by these parameters. The mean detection distances corresponding to the 4-foot stripes for each of the nine cylinder sizes are provided in Figure 1, the mean detection distances for the 8-foot stripes are shown in Figure 2, and the mean detection distances for the plain cylinders are presented in Figure 3. The specifics of this investigation are contained in a technical report by Warner, Hubbard, and Serfoss (in press).

The objectives of the second investigation in the study series were to evaluate the effects of AOI FOV and resolution on visual detection performance and head movements in a simulated low-level target detection task. For this investigation, a visual database was modeled that contained both target and nontarget stimuli. The targets were striped cylinders, as previously described, and the nontargets were plain cylinders without stripes. Six different cylinder sizes were used, which were formed by the combination of three cylinder heights (50, 75, and 100 feet) and two cylinder diameters (25 and 75 feet). The target cylinders were modeled with a 4-foot stripe. One cylinder was place every 2,000 feet along the flight path and the order in which the cylinder sizes appeared was randomized. In addition, the cylinders were randomly placed 1/3, 2/3, and 1 mile on either side of the flight path. The area of the visual database containing the cylinders was 33 miles long. Each observer was provided nine trials, and there were four target cylinders in a trial. Each of the target sizes was presented at each of the six target locations over the nine trials, and the order of the target sizes and locations was randomized. The observers were required to scan the visual environment and press the cockpit gun trigger as soon as they detected the targets. The observers did not have control of the aircraft. The simulated aircraft traversed the database at a speed of 500 knots at an altitude of 150 feet. Target detection distance, offset angle, and detection errors were collected, as well as head movements. Head movements were measured with a Polhemus head-tracking system. The observers consisted of six U.S. Air Force instructor pilots and six nonpilots. Each of the observers performed the task with the small, higher resolution AOI and with the large, lower resolution AOI.

The data have been collected, and the target detection and head movement data are currently being analyzed. A technical report will be prepared addressing this investigation.

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DISPLAY IMAGE QUALITY: SCALING OF CONTRAST, BRIGHTNESS, AND RESOLUTION

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Visual displays used in flight simulation cannot currently provide the fidelity available to pilots in actual out-the-window scenarios. With improvements in technology, though, designers of simulators have increasingly more options in the choice of simulator displays, ranging from helmet mounted displays based upon fiber optics or small cathode ray tubes to large dome (10-20 ft radius) displays which typically employ multiple projection systems. Methods, measures, or metrics are needed as aids to the decision making process for display designers and procurers.

In choosing a display for a particular training or simulator application, it is important that the performance capabilities or quality of the display be represented in a fashion which users can apply as a criterion against their requirements. For example, in air intercept tasks, users may require that detection occurs at a range of five miles, implying a visual angle of approximately three arc minutes for a 20 foot target. The user simply wants to know whether this three arc minute target will be visible. The goal of this approach, then, is to provide an interactive computational tool for making such predictions based upon both physical display parameters and psychophysical data.

An alternative, more gestalt approach in defining image quality originates with viewer preferences. This approach uses paired comparisons, forced-choice measures, and magnitude estimation or scaling in determining observer preferences. As complex as such a multidimensional process is to model, it is a relatively simple task for observers to view two displays and make preference judgments. Although this subjective preference approach is less task-specific than the performance approach, it has high face validity by definition and one typically expects a reasonably high correlation between viewer preference and performance-based approaches to determining image quality.

Current research being done at Armstrong Laboratory at Williams AFB is using both approaches noted above to: (1) build personal-computer based software which allows users to provide physical display characteristics and make queries about static performance capabilities (i.e., detection, recognition, orientation, and identification of targets) and (2) test and develop metrics or numerical measures of image quality aimed at predicting viewer preferences.

The PC-based software is an effort to provide a simple, straightforward instrument from which users can gain insight as to the visibility of targets on a specific display system based only

upon physical parameters for the display which are supplied by the user. The menu-driven software will allow a user to pick a target for display (image #1 - high definition image). Next, given a user input for target range, the target will be displayed over the visual angle it will subtend at the range specified (image #2 - small pixel representation). Then, based upon user input denoting resolution characteristics of the display system of interest and the target range, a blow-up of image #2 will be made which shows what features from the target can actually be represented by the display of interest at the designated target range (image #3 - pixel blow-up). Figure 1 shows an example of the three images displayed on a single, high resolution screen. Note that the pixel blow-up is performed with rectangular pixels. One limitation of the representation is that the display employed for showing the imagery must have better resolution than the display being simulated. Otherwise, it would be possible for an image to be resolvable on the simulated display but not the PC display.

The pictorial representation in Figure 1 provides the user with practical information with which to make display procurement decisions. The images in Figure 1, however, are not corrected for luminance or contrast so only actual stimulus size and feature content are mapped onto the images in Figure 1. The capability to make performance predictions (e.g., detection, heading, recognition, identification) depends upon the local luminance and the target-to-background contrast as well as the visual angle subtended and the resolvability of target features.

A variety of theories exist concerning the required target information necessary for different levels of visual performance. The software currently being developed will assume that all levels of visual performance depend only on the detection of a feature (e.g., the entire target, the nose of an aircraft) designated by the user. The luminance, contrast, and visual angle subtended by the feature of interest will then determine whether the task can be accomplished, or alternatively, given luminance and contrast, the software will estimate the range at which the task may be performed. The software will use previous detection performance data (e.g., Blackwell, 1946) to estimate detectability curves based upon luminance, contrast, and visual angle parameters.

The software described above provides a practical tool to be used in display procurement or design. Alternative approaches may be used which are more quantitatively oriented. These image quality measures focus on the integration of physical display parameters, weighted by the natural characteristics of the imagery and the observer, into a numerical metric from which the relative image quality of a display device may be ascertained. To date, these metrics have focused on the display Modulation Transfer Function (MTF) as the primary display parameter of interest and include display luminance in an indirect fashion. The Modulation Transfer Function Area (MTFA) (see Snyder, 1985) and the Square Root Integral (SQRI) (Barten, 1987) are two image quality metrics which use the display MTF and observer Contrast Sensitivity

Function (CSF) as components in a function which is integrated over the spatial frequency range of the display. These metrics are used as examples of two ways in which the display MTF is differentially weighted over the spatial frequency axis according to image and observer characteristics.

At Armstrong Laboratory, experiments and analyses are being performed which are aimed at: (1) determining the relative importance of the display MTF and luminance in perceived image quality and (2) finding appropriate ways to weight metrics composed of display parameters based upon the characteristics of the image and the observer. Static images are digitized and filtered using mathematically represented display MTFs. Presentation and comparison of these filtered images on a high resolution display yields an estimate of change in perceived image quality as a function of change in the display MTF. Preliminary results indicate that small changes in display MTF are overemphasized in numerical metrics and that display luminance should play a greater role in metrics relative to the current emphasis on display MTF in these metrics. Experiments are planned which will also factorially vary display MTF along with display luminance in determining the relative importance of these parameters to perceived image quality.

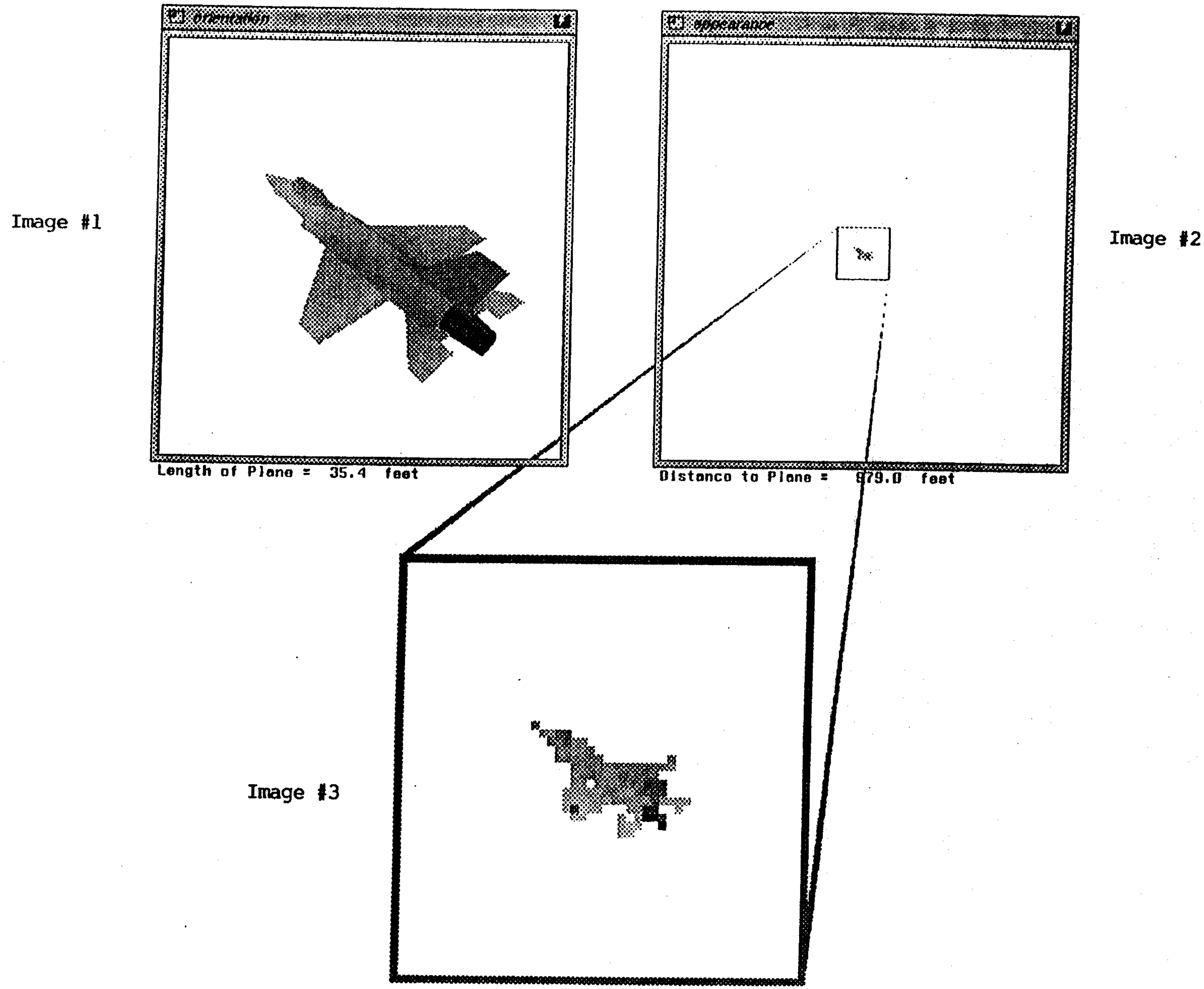

Figure 1. Image Generation

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PSYCHOPHYSICAL ASSESSMENT OF WIDE-FIELD, VARIABLE-RESOLUTION IMAGERY

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Introduction

The information processing capability of the human visual system decreases from the center of the visual field to the visual periphery. The quantitative nature of the decrease depends on the visual task being performed. For instance, the capability to perform simple luminance or contrast discriminations decreases less with eccentricity than the capability to perform certain spatial localization tasks. In any case, a so-called cortical magnification factor (CMF) can be specified which relates the sensitivity at a given retinal eccentricity to that at the fovea. The CMF is presumed to reflect the relatively greater number of cortical cells associated with a given retinal area near the fovea as compared to an equivalent area in the periphery. Thus it follows that the number of cortical cells stimulated can be equated for stimuli in the center and periphery if the latter are appropriately increased in size.

A number of CMFs can be used to estimate a cortical magnification function (CMFn) which will specify how visual sensitivity changes for a particular task across the visual field. CMFns estimated by anatomical and psychophysical techniques have been shown to be consistent for many simple visual discriminations. More recent evidence has suggested, however, both quantitative and qualitative discrepancies between the anatomical and perceptual data especially when more complex stimuli are used. In order to determine whether different perceptual CMFns are associated with the discrimination of complex texture stimuli, we have used wide field-of-view, variable-resolution images to estimate the minimally detectable degradation in image fidelity with retinal eccentricity.

Method

Stimuli and Apparatus. Two real-world aerial photographs were first digitized and then processed using a special-purpose program which locally bandlimited (i.e., blurred) the image as a function of radial distance from the center. The processing was performed with position-varying Gaussian integrating kernels. Linear functions (see Figure 1) were chosen to vary the parameters which specified the integration kernel as a function of distance from the center of the image. These functions were chosen to approximate, to varying degrees, a CMFn which was derived from anatomical data and which was consistent with several previous psychophysical studies. In the first study, each image pair (see below) covered a circular area that was 80 degrees in diameter. In the second study, segments of the original images were used. The radial dimension of the segments was 8 degrees and their angular dimension was varied between 3.3 and 67.5 degrees. All stimuli were presented for 150 msec.

The processed stimuli were presented using a Barco projector and a ground-glass screen. One half of each stimulus was always the original image. On one-half of the trials, the other half of the stimulus was a mirror image of the original, while on the other half of the trials, the other half of the stimulus was one of the series of progressively more processed images derived from that original.

Procedure. Following a period of adaptation to the ambient illumination of the experimental room, the observers were shown the stimulus pairs and were asked to respond as to which side of the stimulus appeared to be more highly processed (i.e., more blurred).

Results

The discrimination data obtained from all three observers are summarized in Figure 1. The four plots associated with each observer correspond to the four sets of variable-resolution functions tested. Based on the percentage of correct responses (%C), three levels were used to categorize the observers' ability to discriminate an unprocessed image from an image processed according to each of the functions within each set. The dark-shaded areas of Figure 1 encompass the variable-resolution functions that were discriminated more than 85% of the time, while the white areas encompass the functions that were discriminated at near the chance level. Discrimination percentages between these extremes were defined as being at or near threshold and are associated with the stippled areas shown in the figure.

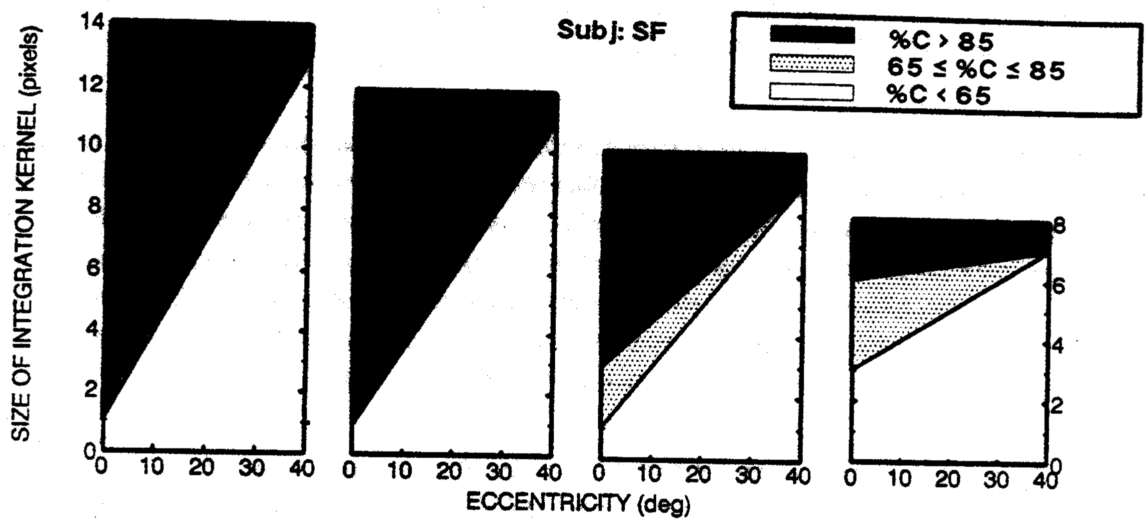
Observer SF was able to discriminate the low-pass filtered images somewhat better than observer GG who in turn was somewhat more sensitive than observer KV. Despite these quantitative differences, all observers showed qualitatively similar patterns of sensitivity across the four sets of stimuli tested. For instance, whereas discrimination performance declined as the size of the integration kernel applied to the peripheral edge of the image was decreased, the decline could be compensated by a (generally smaller) increase in the size of the kernel used at the more central edge of the image. The variable-resolution functions which were estimated to be at or near threshold, for each observer, bear some resemblance to CMFns estimated from simple contrast sensitivity data--although the metric most appropriate for comparing these two types of data remains to be determined.

Conclusions

The slope of the CMFn that produced a minimally discriminable image was very similar to the slopes estimated from luminance and contrast sensitivity data. Thus the discrimination of low-pass filtered (i.e., blurred) images appears to be largely dependent on image properties defined by such fundamental measures as component spatial frequency and orientation.

Similar discrimination data have been obtained for several visually-diverse, complex images, suggesting that the visual equivalence of variable-resolution images is independent of local variations in image detail.

The contribution of various parts of a low-pass filtered image, to the visual discrimination of image blur, summate in the sense that more blurring in the periphery can compensate for less blurring near the center of the image and vice versa. However, the preliminary results of the segmented-image study indicate that the summation area for these stimuli, if it can be defined at all, does not change in accordance with the CMF estimated from full-field images.



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%C < 65
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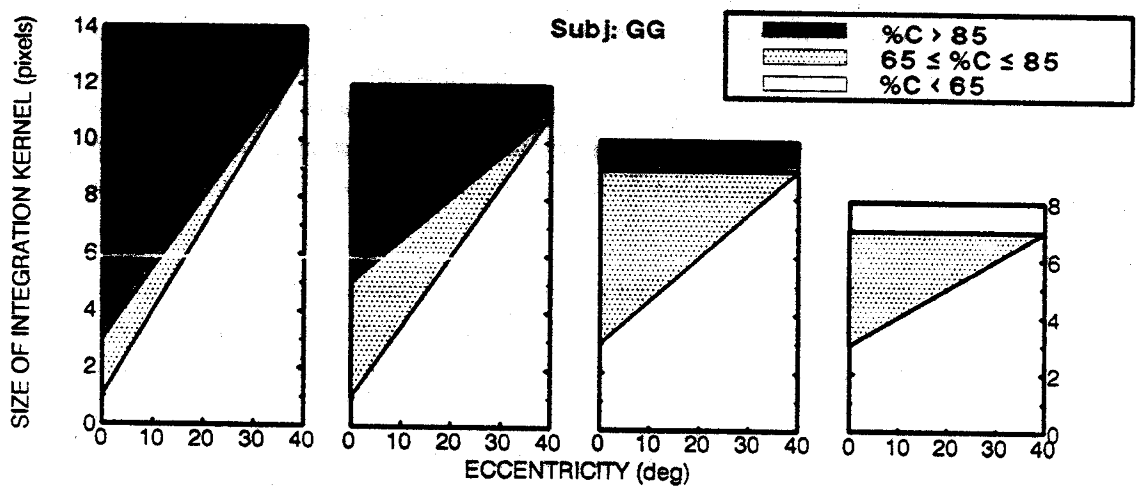

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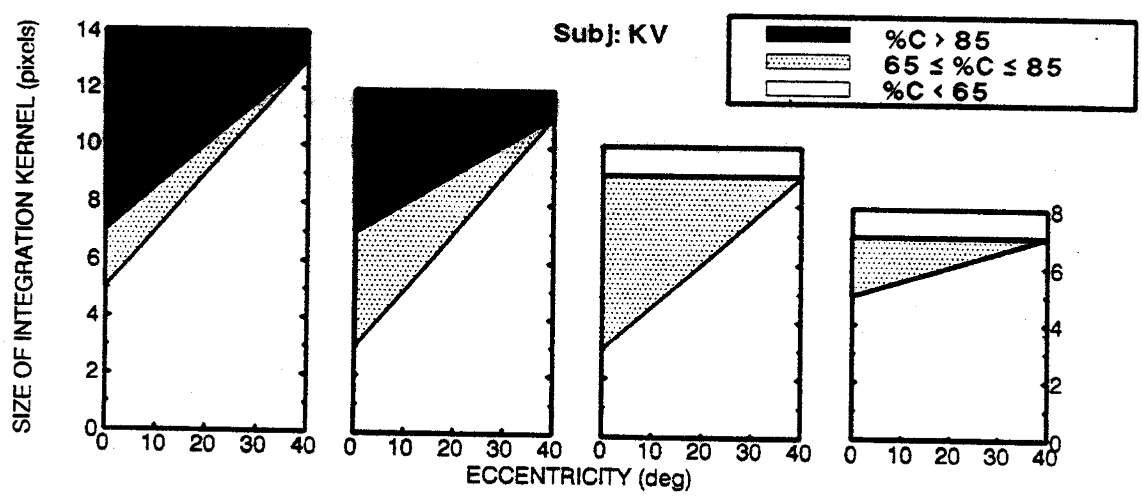

Subj: KV
%C > 85
65 ≤ %C ≤ 85
%C < 65
SIZE OF INTEGRATION KERNEL (pixels)
ECCENTRICITY (deg)

Development and Evaluation of an Eye Measurement System for Flight Simulation

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Introduction

Experimental evaluations of eye tracking measurement systems for use in area-of-interest display systems, have been conducted in an attempt to quantify their performance (Longridge *et al.*, 1989 and 1990, Wetzel *et al.*, 1990a and 1990b). One important result from these studies has been the selection and further improvement of an eye measurement system for use in the Fiber Optic Helmet Mounted Display (FOHMD). An experimental approach for evaluation of a two-dimensional CCD array eye tracking system based on a knowledge of oculomotor behavior for data collected under controlled laboratory conditions and from the FOHMD is described. The results of these experiments have been used as a guide for further development and improvement of the eye tracking system for use with the Fiber Optic Helmet Mounted Display.

In order to evaluate the performance of an eye tracker, it is important to be able to separate and distinguish oculomotor behavior from eye tracker behavior. It is well known that the function of the oculomotor control system is to accurately align and stabilize the high resolution portion of the retina known as the fovea with a visual target or point of interest. Images of objects or points of interest that fall beyond the foveal area of approximately 2mm diameter, or about 5° of visual angle, are poorly resolved. The difference between the image of the target on the retina and the fovea can be thought of as an error signal that provides the driving signal behind many characteristic eye movement responses. Generally, if the retinal error signal between the target object and fovea is greater than 0.5°, eye movements are made to reduce the difference error (Wetzel, 1988).

Materials

The eye tracking system was used to measure the eye position of subjects in response to step changes in target position along the horizontal, vertical and oblique display axis. The difference between target position and measured eye position was then used as a method for assessing the accuracy of the eye tracking system. It was assumed therefore, that position errors greater than 0.5° that were not reduced by corrective eye movements were most likely attributable to the eye measurement system and not to the oculomotor control system. Residual errors that remained after stable eye position had been achieved were likely to be a result of inaccuracies in the eye tracker which allowed characterization of its performance.

A diagram showing the basic components of the Fiber Optic Helmet Mounted Display (FOHMD) is shown in Figure 1. The FOHMD provides high brightness, wide field, high

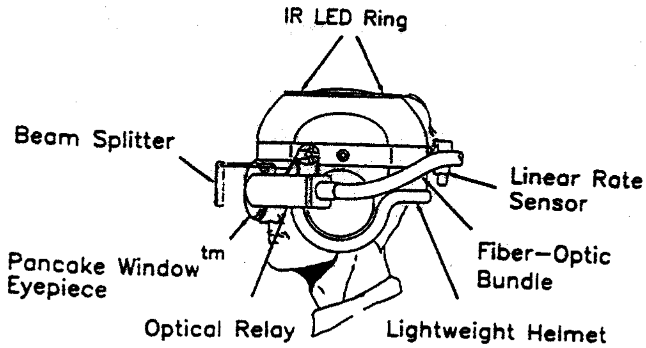

Figure 1. Components of the CAE Electronics Fiber Optic Helmet Mounted Display shown without the eye tracking system.

and low resolution computer-generated color collimated imagery to each eye via coherent fiber optic bundles and Pancake Window^{tm} eyepieces. The computer generated imagery that is seen by the wearer of the helmet is determined by the combined measurement of both head and eye position. The position of the head is measured by an optical head tracking system which determines the location of the low resolution background imagery while eye position determines the location of a smaller high resolution inset. The field of view of each eyepiece and the region of high resolution inset movement is shown in Figure 2. The instantaneous field of view from both eyepieces is 127°H by 67°V with a maximum binocular overlap of 38° at the center. Within the central field of 60°H by 40°V, signals from the eye tracking system are used to control the location of a smaller rectangularly shaped 25°H by 19°V high resolution inset. To minimize the change between the high and low resolution areas a video blending technique is used to smooth the transition between them.

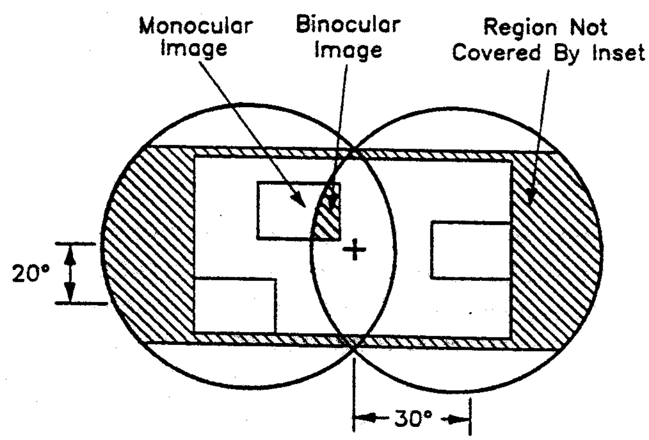

Figure 2. Field of view of the helmet mounted eyepieces and the area of high resolution inset movement as controlled by eye position. The range of inset movement is $\pm 30°$H by $\pm 20°$V.

The optical components and two-dimensional CCD sensor array of the eye tracker mount to the left eyepiece frame of the helmet as shown in Figure 3. The eye tracking system outputs estimates of eye position at 60 Hz using a dark pupil technique. Three IR

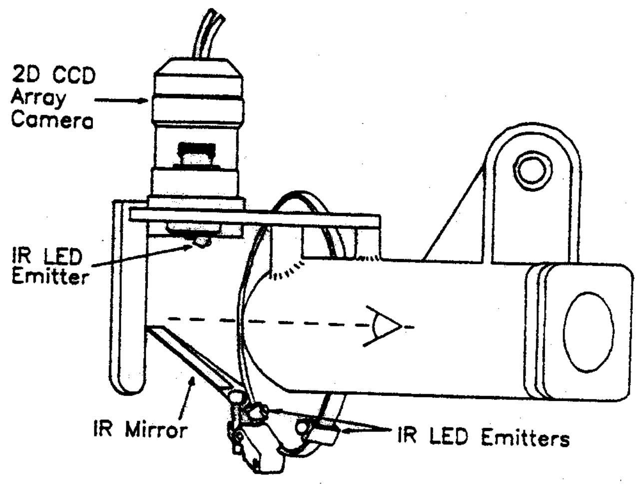

Figure 3. Eyepiece components of the 60 Hz CCD two-dimensional array eye tracking system. The three LED IR sources illuminate the eye and serve as corneal reflection points for the dark pupil eye tracking system. Algorithms utilize an estimate of pupil center and corneal location in order to estimate eye position and compensate for helmet slip.

LED sources fixed to the eyepiece frame illuminate the eye with less than 1 mW/cm^2 of radiated energy and also serve as the corneal reflection points. The relative change between pupil center and corneal positions provides sufficient information for discrimination between eye movement and helmet slip. Infrared light reflected from the eye passes through the eyepiece lens to a dichroic mirror which directs the IR image of the eye to the two-dimensional CCD array camera located directly above. Algorithms process the eye image and provide an estimate of eye position at a 60 Hz rate with a delay of no more than 2 frames. Total weight of the helmet mounted eye tracker components is 50 grams.

Eye position is determined by computing the difference between appropriately scaled signals from the estimated pupil center and the locations of the corneal signals. When an eye movement occurs, the corneal highlights, which are reflections off the nearly spherical surface of the cornea, move at different rates relative to that of the pupil center. When a translation of the eye tracker occurs due to helmet slip, both the corneal highlights and pupil center move at roughly the same rate indicating a translation of the eye tracker rather than a rotation of the eye.

Methods

Eye movement experiments were conducted in both the Fiber Optic Helmet Mounted Display and the laboratory. In both sets of experiments, subjects were instructed to follow as accurately as possible a target while it stepped randomly, in separate trials, along the horizontal, vertical, and oblique axes. Horizontal-vertical stimulus coordinate positions were uniformly distributed over a 0° to ±30° range in two-degree increments. An additional set of stimuli were used to examine small eye movement response along all axis for target displacements less than 1° from center.

Ten observers, all with normal vision, 9 males and 1 female, participated in the FOHMD experiments and five of the 10 subjects, 4 males and 1 female, also participated in the laboratory experiments. An experimental session including scheduled rest periods required approximately one hour and included the presentation of 4 groups of 5 trials each.

All experiments were conducted with room lights off. Prior to each experiment and between groups of 4 trials, a seven-point, ±15° calibration procedure requiring under one minute to complete was performed along the horizontal and vertical axes only.

In the laboratory, subjects were seated a distance of 57 centimeters away from a 1.25H x 1V meter flat display screen while they viewed a rear-projected He-Ne laser target spot that subtended a visual angle of 0.1°. A pair of computer-controlled XY mirror galvanometer motors was used to control the position of the target. Changes in head position were minimized by the use of a molded dental bite bar, head and chin rest support. The FOHMD helmet optics and eye tracker were then mounted to the head support system and the stimulus target was seen through the FOHMD eyepieces. Prior to the start of the experiment, subjects were aligned with respect to the exit pupil of the helmet optics using an external light source. In all experiments, the position of the left eye was measured.

In the FOHMD experiments, each subject wore an individually fitted helmet that supported the aligned helmet optics. The stimulus consisted of an easily distinguishable bright white cross hair that subtended a visual angle of approximately 1.5°. In all trials, the high resolution inset was not used and head tracking was disabled.

Results and Discussion

The collected data from each subject and trial were first inspected with an interactive display program which visually showed the relationship between the stimulus and response. During this procedure, responses which were suspect due to eye blinks or cases where the subject could not locate the target were identified and subsequently eliminated from further analysis. The mean and standard deviation of the sample population response for each trial was then computed by a response averaging program. An analysis program was then used to compute the weighted position error and standard deviation between the sample population response and the actual target position. The sample population results of these analyses were confirmed again by subsequent inspection of the response data with the interactive display program.

The laboratory and FOHMD eye movement responses as measured by the eye tracking system along the horizontal, vertical and oblique axis is shown Figure 4. Apparent directional differences between left-right and/or up-down response, may be attributable to the fact that at the time of system evaluation only the pupil and the nasal corneal signals were used for computation of eye position. Consequently, as the eye rotates farther to the left, the corneal reflection resulting from the nasal IR LED moves closer to scleral surface whose radius of curvature is roughly half that of the cornea. In the present version of the eye tracker, all three corneal signals are contributory in estimating eye position. Thus, if a particular eye position results in a corneal reflection entering the scleral surface, it can be ignored in favor of the other corneal signals.

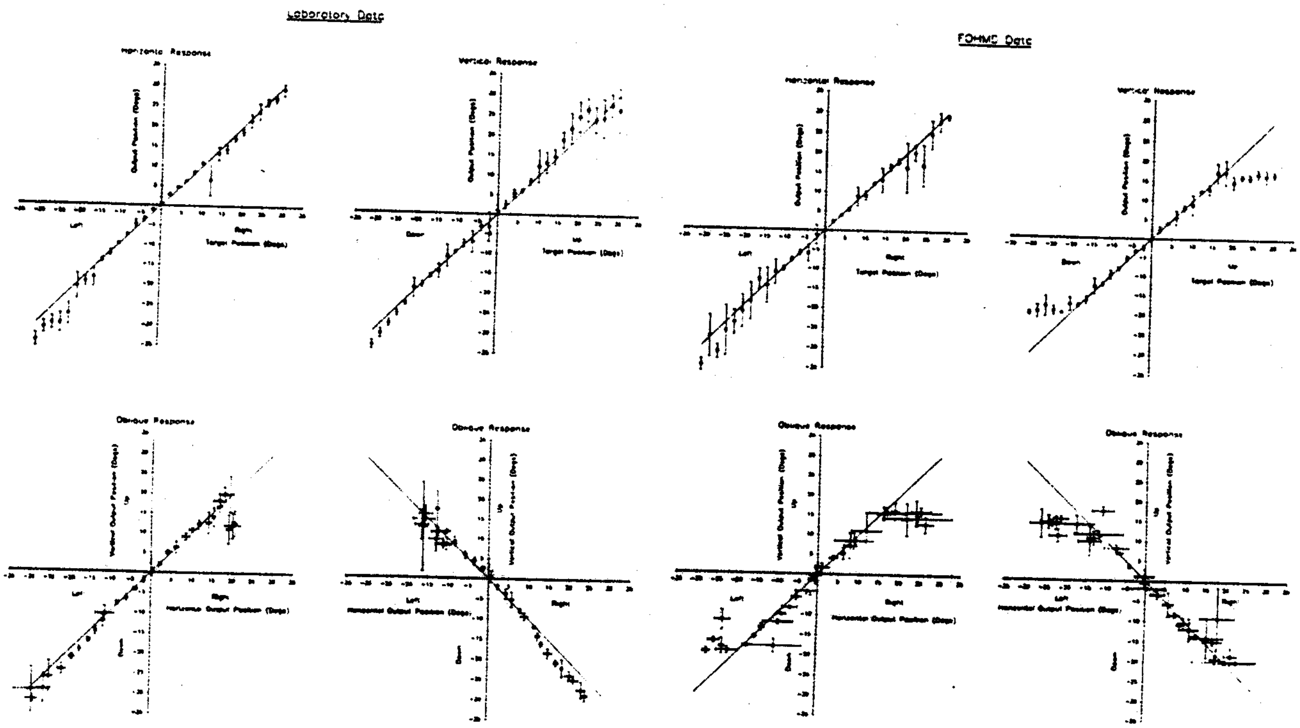

Figure 4. Response data (mean ± sd) for laboratory and FOHMD experiments with the ideal response given by straight line diagonals.

Laboratory data from the small target displacement studies revealed that the eye tracker was consistently able to resolve changes in eye position as small as 0.5°, the signal-to-noise ratio being the limiting factor. A sample recordings of eye position data collected from the same subject and identical stimulus segments under both helmet and laboratory conditions is shown in Figure 5.

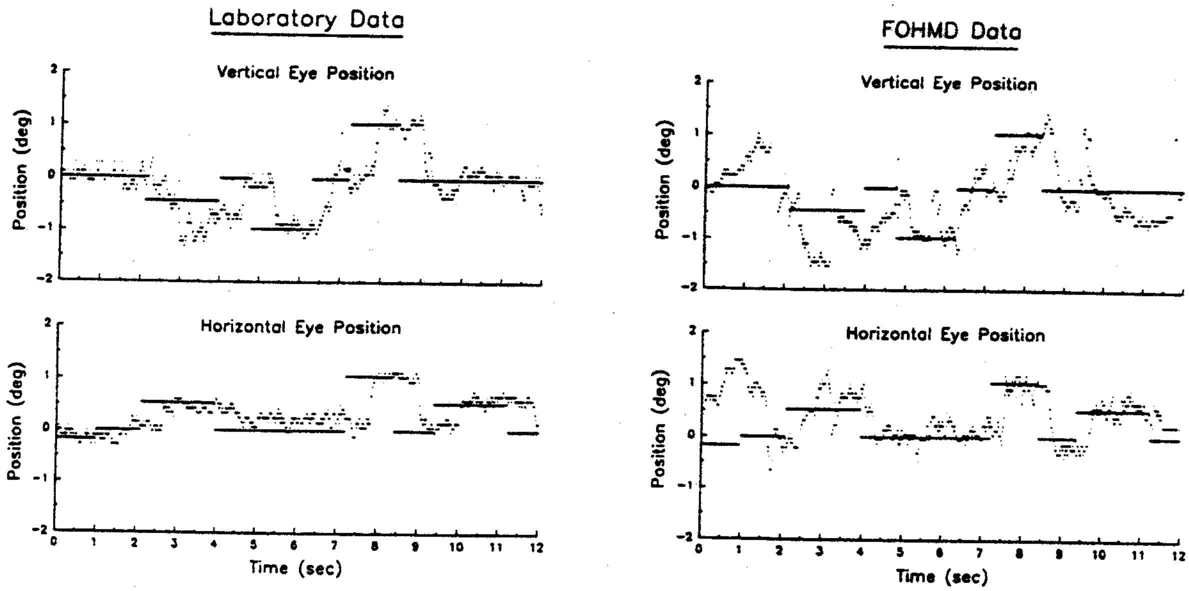

Figure 5. Comparison of the small eye movement response of one subject under laboratory and FOHMD conditions for an identical sequence of target movement.

Under laboratory conditions, head position was firmly stabilized while the head was not during the helmet experiments. The differences between the sensitivities maybe attributable to small amounts of helmet slip or to helmet slip compensation methods. The amount of noise present in the system determines the boundary conditions under which area-of-interest display systems operate. As such, output noise from the eye tracker or other systems will determine the amount of jitter present in the high resolution area of interest. At the present time however, the amount of noise or jitter in the FOHMD is not a serious factor since the size or area of the high resolution inset is considerably greater than that of noise level. However, if the size of the inset were to be significantly reduced, such as in proposed eye controlled variable acuity displays, then the level of noise would become a far more serious concern.

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Acknowledgment

Support for this work was performed under USAF Contract No. F33615-81-C-0012 under a joint US/Canadian Defence Development Sharing agreement.

THE EYE MOVEMENT BEHAVIOR OF PILOTS

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ABSTRACT

This study was designed to determine whether the conjugate eye movement tracking of carrier-based fighter pilots is different from that of controls. We hypothesized that compared to a seamen control group, pilots flying high performance aircraft have superior ocular tracking capabilities because of the highly visual demands of the flying task. We used an infrared limbus tracker to measure the eye movements of 65 subjects in the U.S. Navy (ages 18 to 45 years; 31 pilots, 29 controls and 5 helicopter pilots). All subjects tracked 19 trials of a small (0.4°) line on a CRT (max. amplitude = 17°). All subjects tracked the following waveforms: two square waves (0.25 and 1.0 Hz), two types of random square waves (multiamplitude and ternary), four sine waves (0.1 to 1.0 Hz.), a random smooth waveform and five repetitions of a cubic waveform (1 Hz). The mean deviations (MD; mean absolute value of the eye position vs. the stimulus) for the cubic waveforms were all significantly smaller for the pilots compared to the controls (p= 0.048 to 0.002, e.g., MDs, trial 1: 2.2°, s.d.= 0.4° vs. 2.7°, s.d.= 0.7°). Although the MDs of the eye from the stimulus were generally in the hypothesized direction for the other waveforms, none reached statistical significance. We conclude that there is evidence suggesting that there are differences in the ocular tracking capabilities of these two groups of subjects. These differences may prove useful in the selection, evaluation and/or training of individuals performing complex tasks where vision is a major component.

INTRODUCTION

Flying high performance aircraft requires a high degree of motor coordination considering the high speeds and the cost of errors[1-3]. Decisions at these high speeds must be made quickly and accurately[1-5]. Accurate eye movements are a significant factor in flying[4-6]. Various ocular movements are used to scan the instrumentation in the cockpit as well as to see other aircraft or structures and land the plane.

Presently, although they are generally considered to be significant, the relative importance of accurate eye movements in the performance of a complex visuomotor task such as flying is unknown. Such a question is difficult to answer precisely because there is a large degree of variability between the ocular movement capabilities of normal subjects[8-14]. In this regard, there are a large number of factors which have been shown to effect the eye movement capability of such as the effects of attention and fatigue[8-9, 13, 15-18].

Recently, Daum et al[24] have suggested that professional baseball players have better ocular tracking capabilities than a group of age-matched control subjects. Prior to that study, Bahill and his colleagues[15, 25-26] had made a similar suggestion. Although these studies suggested that there was a difference between the groups, none of them was able to establish the reason for the tracking differences. Also, these studies could not determine whether the differences in eye movement capability between the groups were a result of a selection process or whether they were a result of experience related to the differing visual demands between the groups.

The purpose of this study is to determine whether there are ocular tracking differences between two groups of individuals with radically different visual demands: carrier-based fighter pilots in the U.S. Navy and seamen assigned to a U.S. Navy carrier. If there are differences between these groups, then it is likely that further investigation may allow eye movement capability to be a useful factor in the selection and/or the training of aviators and groups with similar visual demands.

METHODS

Subjects

All pilots were selected from four squadrons of carrier-based pilots in the U.S. Navy. Control subjects were recruited from among seamen serving upon the aircraft carrier U.S. America where the majority of the data collection took place.

Stimulus and Eye Movement Measurement

The stimulus was a computer-controlled fine green line (0.4° in length) moved electronically about the face of a cathode ray tube (CRT; Tektronix Model 604; Beaverton, OR). Data were recorded from both eyes using an infrared limbus tracker[16] (Applied Science Laboratories Model 200; Walthan, MA).

The basic measure of tracking ability used to compare the two groups for all waveforms was the **mean deviation (MD)**. This is the square root of the mean squared retinal error[15, 25-26]. Fourier analysis and cross correlations of the data were also used where appropriate.

RESULTS

We recruited a total of 65 male subjects between the ages of 18 and 45 years. The pilot group had a statistically greater mean age than the other groups ($F_{(2,62)} = 4.99$, $p = 0.01$).

Figure 1 shows MD and its associated 95% confidence limits for each of the waveforms for the two groups. Probability values for the hypothesis of differences between the groups are shown in parentheses. Differences between the groups in tracking the cubic waveform were significant: the pilots had smaller errors ($F_{(2, 59)} = 3.26$; $p = 0.04$).

Figure 2 shows MDs for the cubic waveform for the pilots and controls for the five trials. The pilots started with a smaller MD which remained consistently below that of the controls by about 0.3 to 0.4°, a 15 to 20% smaller error. There was a significant trial effect ($p = 0.05$) suggesting that the MD of the groups decreased with practice (i.e., they learned the waveform). At the same time, there was not a significant interaction between the group and the trial ($p = 0.83$). This suggests that the groups learned the waveform at the same rate. On each trial, the significance level (p) for differences in MD between the groups ranged from 0.01 (trials 1 and 2) to 0.29 (trial 4; Kruskal-Wallis tests).

Figure 3 shows cross correlograms averaged over all of the trials of the cubic waveform for the pilots and the controls. This suggests that the pilots were better able to match the trajectory of the target with the eye.

Figure 4 shows periodograms averaged over all trials of the cubic waveform for the pilots and the controls. The pilots do not show any greater tendency toward matching the stimulus periodogram than do the controls. This suggests that the pilots do not generally follow certain stimulus components of the waveform better than the controls.

DISCUSSION

This study suggests that the oculomotor tracking capabilities of carrier-based pilots are superior to the seamen serving as a control group. The pilots tracked the cubic waveform significantly better than the control group. This waveform, possibly because it does not exist in nature and therefore negates the effects of experience, was hypothesized as the most likely tracking task where differences in capability would be detected. The primary reason that the pilots were superior to the controls was that they were more consistent than the controls. This is shown in the cross-correlation analysis of the cubic waveform: the pilot's distribution is of larger magnitude and is narrower.

This group of pilot's oculomotor capabilities were not uniformly superior to those of the control group. In contradistinction to professional baseball players[24], the pilots did not follow the faster frequencies more proficiently.

Taken together with the results of previous studies by Daum et al[24] and Bahill and colleagues[15, 25-26], these suggest that certain groups of individuals have better capabilities in tracking than others. In contrast to the pilots, the professional baseball players appear to have smaller mean tracking errors primarily because of a greater capability to track the faster components of the waveform[24].

This study also suggests that it would be appropriate to study the relationship between eye movement capability and training. In particular, a part-task training approach to aviation activities requiring fine control of the eyes may prove useful. Obtaining improved ability to control the eyes through training may allow better performance in the overall task.

ACKNOWLEDGEMENTS

This work was supported in part by grants from the School of Optometry of the University of Alabama at Birmingham and a Biomedical Research Support Grant from the National Eye Institute (BRSG S07 RR05807).

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FIGURES

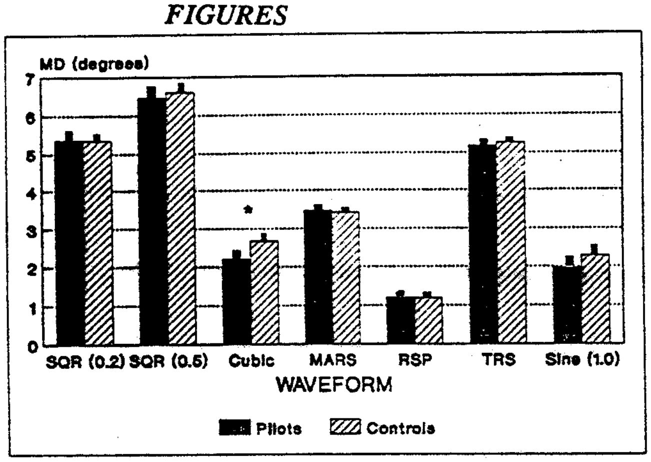

Figure 1

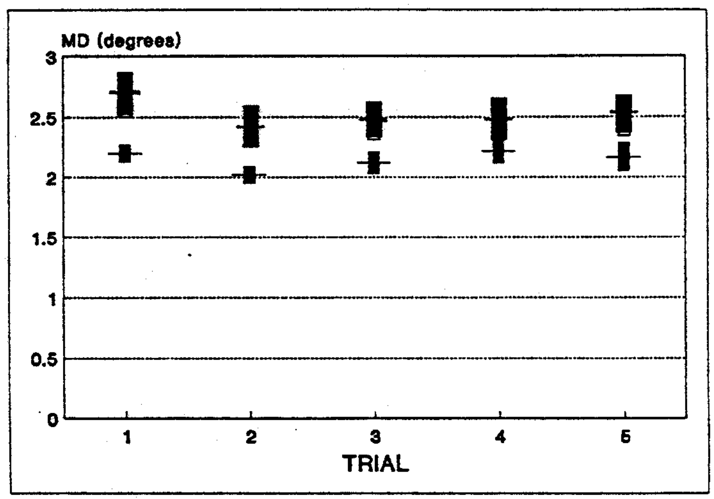

Figure 2

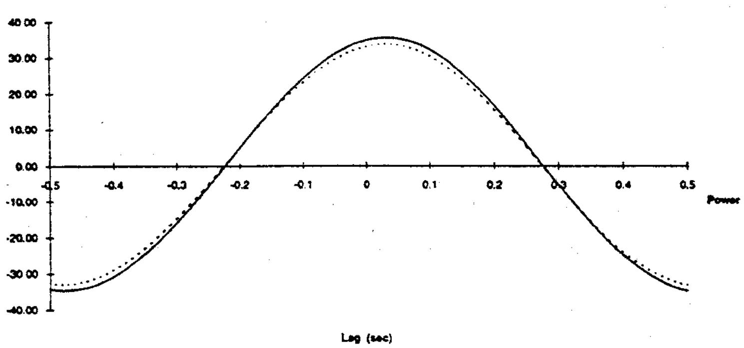

Figure 3

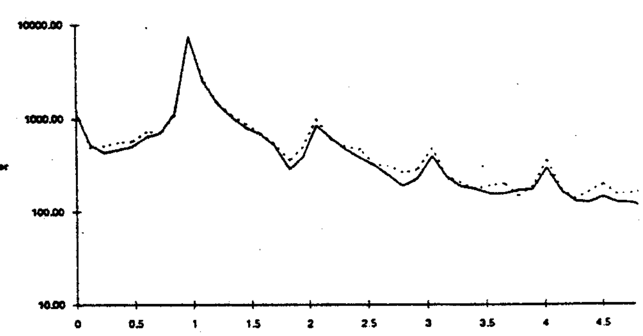

Figure 4

VISION AND VISIBILITY ISSUES IN U.S. NAVY LANDING CRAFT, AIR CUSHION (LCAC) CREW PERSONNEL

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The Landing Craft, Air Cushion (LCAC) is the U.S. Navy's newest high speed, high technology, amphibious assault craft. This state of the art hovercraft has made rapid over-the-horizon (OTH) support possible for over 80% of the world's beaches. Conventional assault craft could only travel up to 8 knots and negotiate only 17% of the world's coastlines. The LCAC can travel at speeds over 40 knots at sea and 25 knots on land, and can surmount land obstacles of up to four feet in height. The LCAC is a ship-to shore vehicle that can transport 60 tons up to 50 miles. Unlike conventional craft, the LCAC is not affected by tides, water, depth, underwater obstacles, beach slopes, torpedoes, or most mines. This highly capable vehicle has revolutionized the design of military amphibious operations. Similarities and differences exist between LCACs and rotary-wing aircraft. Similarities include LCAC capability for three-axis motion (including lateral traverse), speed beyond that of surface craft, nature of operating controls (yoke, collective, and foot controls), high-performance propulsion systems (four gas turbines), and advanced navigation and engineering displays. Differences include less operating altitude (four feet rather than thousands) and speed (40 versus 160 knots) compared to helicopters, fully shrouded rotors that allow closer approaches to objects, and a crew that is larger and more interdependent than that of a helicopter, but lacking the capability for one-man craft operation. LCAC operating characteristics and technology have created unique mission conditions and performance requirements for crew personnel.

The operational requirements of this sophisticated amphibian and the premium upon retention of highly trained crew personnel led to the establishment of specific (interim) physical standards for LCAC crew. The development of permanent medical standards is underway. Due to the craft's numerous operational similarities to aircraft, U.S. Navy aviation medical selection criteriae were used as the basis for the interim medical standards. During the standards development process, significant consideration was given to minimum visual acuity limits, particularly for craft operators. This emphasis came partly from aviation community input, and partly from those involved experienced in LCAC operations and familiar with the visual needs of craft personnel.

Vision/visibility, total workload, and cockpit resource management are considered to be key interrelated human factors issues. Navigation and effective LCAC craft operation are highly dependent upon visual cues. Visibility from these craft when operating on air cushion is almost constantly degraded by water spray, dust, and occlusion by the craft structure itself. In terms of visibility, operating an LCAC has been compared to "driving an

automobile in a rainstorm". Craft approaches to the beach and to the "well deck" (operations bay) of the support ship are where the highest workloads and potential for error occur. Identifying the beach landing site and maneuvering while ashore is a group activity. Locating beach obstacles, depressions, etc. include constant visual searches performed while moving at relatively rapid surface speeds. There is a perceived increase in cockpit workload due to further visibility decrements during nighttime operations, which comprise a significant percentage of LCAC missions. Beach approaches during night operations take on a special quality of crew vigilance, as does the avoidance of surface obstacles en route to these night landings. Currently available night vision devices have been minimally effective in improving night visibility for craft operators. Visibility does appear to be a primary performance limiting factor for LCAC crews. Degraded visibility increases total cockpit workload and is an important issue in cockpit resource management for this highly interdependent team. Other workload issues, such as the fatigue resulting from fast-paced turnaround missions, are additive to the demands of vision and visibility. Whether current minimum visual acuity standards for LCAC candidates are optimal or excessively selective in light of diminished operational visibility is a question currently under investigation.

Visibility issues for LCAC personnel to be developed include the following:

1. The collection of objective vision and visibility data under real or simulated mission conditions, and relating that to task performance. Current recommendations are based on subjective observations, and are not quantitated.

2. Training techniques to enhance individual processing of degraded and night visual cues. Although selection criteria have been adopted to minimize the possibility of visual errors in crew personnel, the issue of possible enhancement of individual capability has not been addressed.

3. Identifying an effective means of screening LCAC candidates for their relative ability to recognize degraded visual cues. Current night vision screening for example, is limited to the history of difficulty with night vision.

4. Possibilities of improved night vision devices. LCAC personnel who have used the night vision devices currently available to these units have experienced a number of difficulties with them related to loss of peripheral vision, instrument glare, etc. Different personal devices, or a different system such as craft-mounted forward-looking infrared (FLIR) have been suggested.

5. Setting optimal visual acuity standards for LCAC crew personnel. This is one of the tasks involved in the current development of the permanent medical standards.

CONTROL AND USE OF COLOR IN FLIGHT SIMULATORS

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University of Dayton Research Institute
Armstrong Laboratory, WAFB

My talk will survey the laboratory's program of work on display color, which has given priority to the problem of color control because until display color is adequately controlled you can't do research on the use of color. However, we have also been concerned with problems relating to the use of color, and I hope to spend most of my time talking about current approaches to these problems.

I have reviewed the problem of color control in digital displays in a chapter written for a forthcoming book, Electro-Optical Displays, edited by M. A. Karim. That chapter is too long to review here; it is based on an extensive search of the literature and 5 years of work with our own laboratory displays. But, in a nutshell, it reports the prevailing consensus that color control must make use of a common, internationally accepted reference system, namely, one of the descriptive color systems adopted by the CIE and based on XYZ tristimulus values.

The diagram in Figure 1 was adapted from Roy Hall's 1988 book, Illumination and Color in Computer-Generated Imagery, and it reflects this consensus. Although "Current Practice" still relies upon RGB computation and storage of color data, everyone should now recognize that RGB color differs from one display device to another. In other words, RGB color is device-dependent. For adequate control, the "Ideal Methodology" requires that color data --from whatever source--be transformed to a CIE XYZ-based color

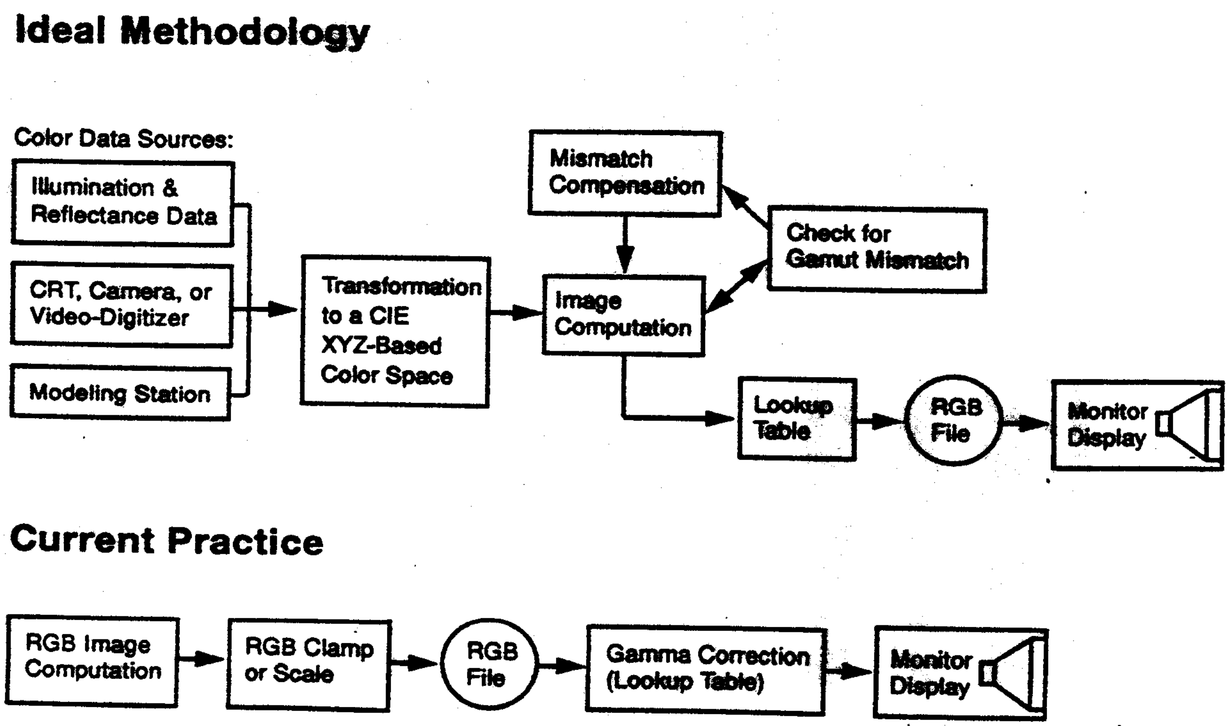

Figure 1.

space before image computation and that the resulting color data be transformed to the device's own RGB digital codes at the last possible moment before display. The diagram contains much more detail which I will not tarry to discuss, except to urge that as much as possible, as soon as possible, the simulator community should adopt "Illumination & Reflectance Data" as the principal source of color information going into flight simulation databases.

For those of us still stuck with image generators that compute color data in RGB space, there is a practical approximation to the Ideal Methodology. We can adopt a color-editing system which works in an XYZ-based space and which computes the corresponding RGB digital codes from information about our display device's color output characteristics. Corporations in the color reproduction business are beginning to present such color editors on the market; Tektronix, for example, is marketing the Tektronix Color Management System (TekCMS™) for use in the reproduction of computer-graphics images on color printers.

Figure 2 shows an on-screen display from our laboratory's Color Modeling Workstation, still under development, which will enable us to specify the XYZ-based colors in each of our many databases in RGB digital codes <u>tailored specifically to each of our several display devices</u>. This color-editing system, like TekCMS™, makes use of an approximately uniform chromaticity space called CIELUV, which was recommended by the CIE in 1976 as one of two such spaces (the other one is called CIELAB) which may be used to show the relative positions of colors in 3 dimensions. Those of you interested in the Color Modeling Workstation will have an

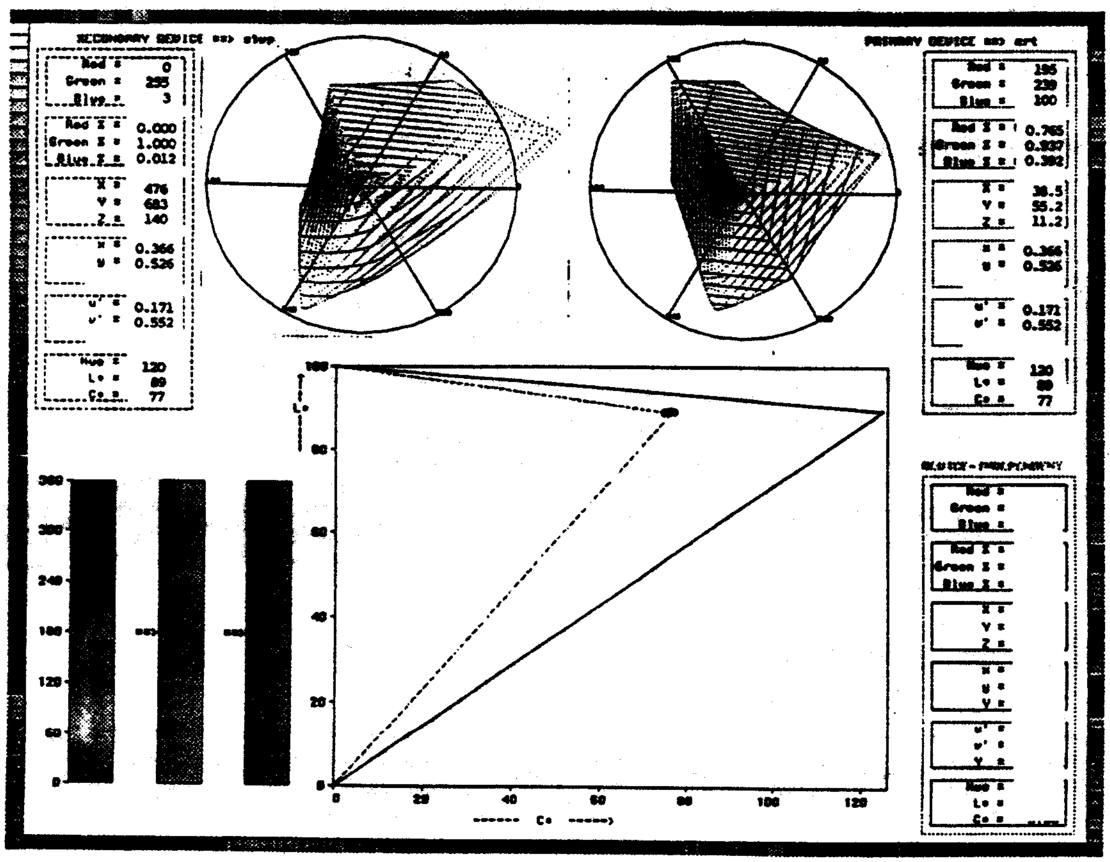

Figure 2.

opportunity to see it this afternoon and ask questions about the information which it displays.

When the problem of color control has been solved, I can be confident that the color output of my display device--whatever it is--will correspond <u>physically</u> to the XYZ-based colors which have been specified. I will be able to verify this correspondence by setting up whatever photometer or radiometer is available and taking measurements. Will I then be happy with the full-color display which results? Not necessarily. A lot depends upon the artistry and technical proficiency of the colleague who modeled the database. This "technical proficiency" should be aided increasingly, in the coming years, by developments in the investigation of <u>color appearance</u>.

Color science is presently moving forward from <u>colorimetry</u>, which gave us chromaticity diagrams based on color-matching data and the CIELUV/CIELAB 3D color spaces based on color-difference data. The investigation of color appearance requires scaling of psychological quantities such as brightness, lightness, and colorfulness. The expected product will be a more complete model of human color perception; two such models have already been proposed and are continually being revised and evaluated. Some demonstrations illustrating the difference between colorimetry and color appearance will be included in the oral presentation.

Color scientists working in the photographic industry have been aware of color appearance problems for 40 or 50 years. They have solved some of these problems very successfully by modifying the sensitivity of their color films. Simulator displays have some color appearance problems that are rather like those encountered in the early days of color photography, when the results were commonly viewed as color slides projected with tungsten light in a darkened room.

These problems arise in our industry, as they did in the photographic industry, because we are trying to reproduce "real scenes" under the following limiting conditions: (1) Maximum luminance no greater than about 100 nits, when out-the-window scenes can range up to 100,000 nits in sunlight. [This limitation is much worse for dome displays using light valves, where the maximum luminance is no greater than 10 nits.] (2) A light-dark contrast ratio (L:D) of 30:1 at best, when out-the-window scenes normally have L:D ratios of 100:1 or better. [Again, the case is much worse for dome displays, whose contrast is 5 or 10:1 for most objects.] (3) A limited field of view, perhaps 60 by 140 degrees, in a <u>dark surround</u>.

All these characteristics are common to both photographic slides and simulator scenes. In addition, simulator scenes have two more conditions which affect color appearance: (4) A light-source which is a self-luminous display controlled by a computer image-generator, when out-the-window scenes are generated by light reflected off real objects illuminated by daylight. [Photography also starts from such reflected light.] (5) Spatial and temporal resolution limited by image-generator and display characteristics, when out-the-window scenes have resolution limited by time of day, weather conditions, and the human visual system. [Photography had to deal with spatial sampling (film grain) but not with temporal sampling.]

Low luminance comes at the head of the list, because it is the source of several color appearance problems. The general level of adapting luminance has a profound effect on perceived brightness--and therefore on perceived contrast--as Jameson and Hurvich pointed out in 1961 in an elegant little article in Science magazine. As average luminance in the visual field goes up, the whites not only get whiter but the blacks get blacker; the scale of perceived brightness is expanded, making the light/dark contrast more apparent to the eye. For our simulator displays (and for color slides) this finding explains a major problem. Because our displays are dim, we must, if possible, exaggerate the physical luminance difference between light and dark areas, making them relatively more different than they are in the "real scene," in order to capture the same apparent contrast.

Reduced luminance also means reduced 'colorfulness', a term that is technically not the same as either 'saturation' or 'chroma' but that signifies the richness or vividness of the hues in a scene. A dark surround also serves to reduce colorfulness. In the photographic industry, films have been devised which heighten color beyond the level of mere duplication of the physical chromaticity in the scene. Then, when projected in a dark surround at low luminance, the colors appear approximately as 'colorful' as in the normal daylight scene.

At low luminance levels, and when using self-luminous display colors, the apparent brightness of colors will require special attention. Self-luminous displays can produce higher relative luminances for reds, magentas, and blues than will ever occur in natural scenes. In natural scenes, the most saturated colors occur in low reflectance samples viewed in bright illumination. Although the amounts of light emitted by blue or red phosphors of a CRT are much lower than the amount emitted by the green phosphor, these amounts are still enough to exceed the relative luminance of a saturated blue or red surface reflecting natural light.

If the display is operating at dome display luminance, the light level is also mesopic, and the rods are making a relatively large contribution to apparent brightness. The rod contribution will exaggerate the apparent brightness of the blues, while the cone contribution is still sufficient to make saturated reds appear luminous. These facts mean that self-luminous displays make it easily possible to over-exploit colors near red and blue.

Our investigations now deal increasingly with methods of heightening contrast and colorfulness in the large-screen displays which you will see at Williams. Some of these employ light-valve projectors while others use projection CRTs. The color outputs of these two types of projector are radically different. Their color gamuts are compared in the two insets at the top of Figure 2 (light valve on the left, CRT on the right). The vertical axis in Figure 3 shows the L* (brightness) dimension of these outputs. Simply making maximal use of these very different gamuts requires color-processing through something like the Color Modeling Workstation. Further problems arise from texturing and anti-aliasing algorithms which are still applied in RGB space.

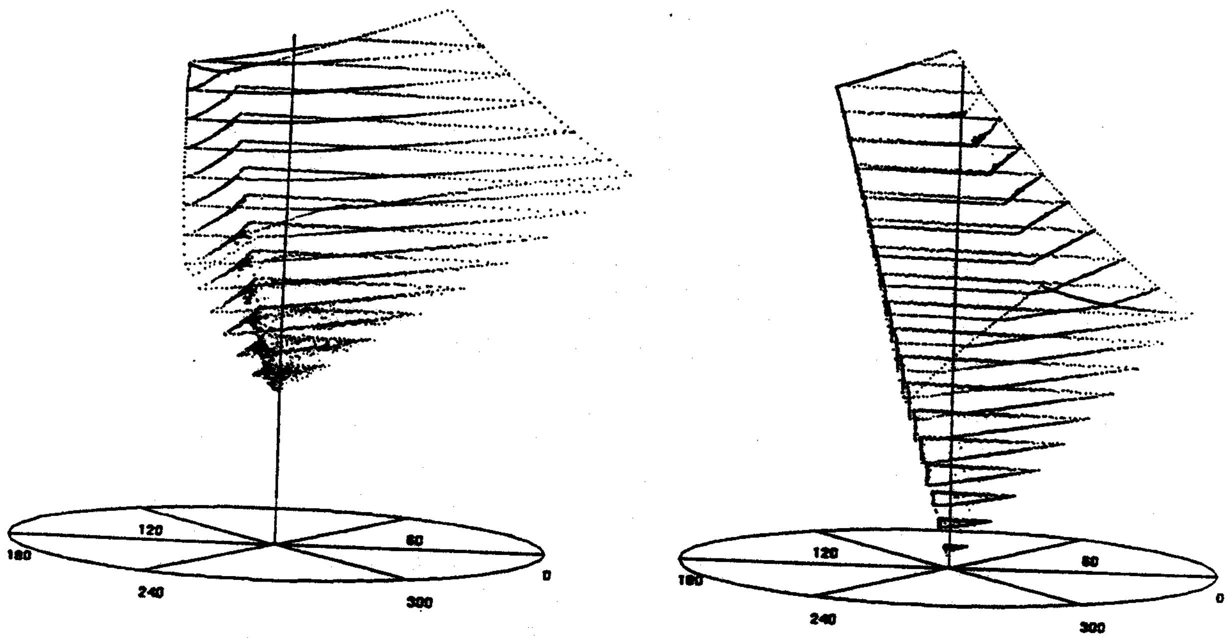

Figure 3.

Full realization of the color potential of existing display devices will probably require innovations in image-generating systems. As these innovations develop over time, our task is to help buyers and users of simulation systems apply appropriate standards in choosing and operating these devices.

DETERMINANTS AND CONSEQUENCES OF SMOOTH PURSUIT

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The visual systems of most flight simulators consist of an image generator (IG) and an electro-optical display device. The IG samples, in both space and time, the distribution of light that would be visible through a "window" orthogonal to the line of sight and in front of an observer who moves through a data- base model of some region of the world. These digital values are converted to an analog signal which modulates the output of the display device. The resulting visual display is meant to reproduce, as closely as possible, the original (if hypothetical) space-time image.

According to sampling theory, the Fourier transform of a sampled version of a continuous function is a periodic replication of the transform of the original function, with the replicas separated by the sampling rate(s). Thus, if the continuous image of an IG, $\underline{f}(\underline{x},\underline{y},\underline{t})$, is sampled in space with intervals of $\Delta\underline{x}$ and $\Delta\underline{y}$ and in time with an interval of $\Delta\underline{t}$, then the replicas will be separated in the $\underline{f}_x,\underline{f}_y,\underline{f}_t$ frequency space by the sampling rates $1/\Delta\underline{x}$, $1/\Delta\underline{y}$, $1/\Delta\underline{t}$, respectively.

A continuous function is bandlimited if its Fourier transform is zero outside some bounded region (the region of support) in the frequency space. Sampling a bandlimited function at greater than twice its maximum frequencies, that is, at greater than its <u>Nyquist rates</u>, ensures that none of the replicas in the sampled function will intrude into the region of support of the original function. The original function can then be recovered from the sampled function by a lowpass filter which completely attenuates the replicas introduced by sampling and passes the baseband (i.e., original) spectrum without attenuation.

If a function is sampled at less than its Nyquist rate for a particular dimension, frequency components representing the original function will extend <u>above</u> and corresponding components of the appropriately spaced replicas will extend <u>below</u> half the sampling rate. This phenomenon is known as <u>aliasing</u>. When aliasing occurs, the original function cannot be recovered by subjecting the sampled function to a low-pass filter with cut-off frequencies equal to half the sampling rates: The high-frequencies in the original function will be lost and aliased frequencies will distort the function that is passed. To prevent aliasing, the original function must be filtered before it is sampled to ensure that it does not contain frequencies higher than half the sampling rates. Appropriate filtering during reconstruction will then result in a lower-resolution but otherwise distortion-free copy of the original function.

Because the data base of an IG consists of polyhedra with infinitely sharp edges, the spatial-frequency content of an image that is derived from that data base will not be bandlimited. Moreover, because the temporal frequency of a moving spatial sinusoid equals the product of its spatial frequency and its velocity, a time-varying image will also contain infinitely high temporal frequencies.

To reduce aliasing, the more advanced IGs have implemented algorithms that serve as lowpass (albeit nonoptimal) spatial presampling filters. However, except for the indirect effects these filters have on the temporal-frequency content of the image, current IG system have not implemented any procedures to reduce temporal aliasing.

Differences also exist in the spatial and temporal filtering properties of standard display devices. For example, the intensity distribution of the electron spot of a CRT serves as a reasonable spatial postsampling filter. In contrast, very little temporal filtering is provided by current CRT phosphors, which typically decay to 10% of their maximum intensity in less than a millisecond.

Computer generated display images are thus characterized not only by aliased spatiotemporal frequency components, due to the lack of an adequate temporal presampling filter, but also by components with temporal frequencies greater than half the temporal sampling rate, due to the lack of an adequate temporal postsampling filter. The inadequacy of the temporal postsampling filter is usually not problematic, however, because the human visual system, which is sensitive to only a limited range of spatiotemporal frequencies, functions as a second postsampling filter. In this regard, Watson, Ahumada, and Farrell (1986) proposed that an observer will be unable to distinguish between a continuous image and a temporally-sampled image if the frequencies in the replicas of the sampled image fall outside the "window of visibility," which they defined as a rectangular frequency space bounded by the spatial- and temporal-frequency limits of the human visual system.

Thus, if a continuous image were subjected to temporal and spatial presampling filters that eliminated (only those) frequencies to which the human visual system is not sensitive and then sampled at frequencies in excess of its Nyquist rates (which, in this case, would also be twice the spatial- and temporal-frequency limits of the visual system), then the resulting display image should be perceptually equivalent to the original, unfiltered image.

If the observer's eyes move, however, the temporal frequency content of the retinal image will not match that of the display image. Therefore, a temporal presampling filter based on the frequency content of the original image is appropriate only if the observer maintains a constant fixation. This is unlikely under free viewing conditions. Smooth pursuit eye movements are elicited by sampled versions of an object moving at a constant velocity,

even when the spectral replicas contain spatiotemporal frequencies to which the visual system is highly sensitive. Indeed, while the work of Watson et al. (1986) suggests that the perceptual mechanisms that interpret the retinal image can distinguish between sampled and continuous motion when frequencies in the sampling-induced replicas are visible, our research indicates that the oculomotor system is insensitive to this information. Stated more positively, the oculomotor system can extract the constant velocity line from quite complex spectra.

Figure 1a illustrates the spatiotemporal-frequency spectrum of a continuous image of a vertical bar moving from left to right at a constant velocity $\underline{v}$. The region of support of the spectrum has a slope of $-1/\underline{v}$; its sinc-like cross section reflects the width of the bar. Figure 1b illustrates the spectrum of a sampled version of the specified image. Note that the original spectrum is replicated at multiples of the sampling rate, $1/\Delta\underline{t}$.

If the bar in the image is taken to subtend a visual angle of 12.5 arc min and to move at 10 deg/s, then Figure 1b represents a sampling rate of 60 Hz and the displayed spectra (Figures 1a & 1b) each cover ± 120 Hz horizontally and ± 12 cycles/deg vertically. Clearly, for this velocity, the spectral replicas introduced by a 60 Hz sampling rate would contain spatiotemporal frequencies that are well within the passband of the human visual system. Moreover, many spatiotemporal frequencies in the original spectrum would not be visible.

If the velocity of the eyes were exactly 10 deg/s, however, then the region of support of the retinal image (for Figure 1b) would consist of vertical lines at multiples of the sampling rate (Hsu, 1985). Each spatial frequency in the baseband would be associated with a temporal frequency of zero. The replicas introduced by sampling would be visible (and then as flicker) only if the observer were sensitive to a temporal frequency of 60 Hz.

Clearly, the spatiotemporal frequency content of the retinal image that results from a given display image varies dramatically with the oculomotor behavior of the observer. We are currently investigating the determinants of that behavior and its perceptual consequences.

For example, we have found that smooth pursuit eye movements of an approximately constant velocity are sometimes elicited by sampled (and probably continuous) versions of images with inconstant velocity profiles. This property of the oculomotor system is of particular importance for display images created by simulators in which the update rate of the IG is less than the refresh rate of the display device. In such images, a representation of a moving target is presented $\underline{r}$ times at every sampled position, where $\underline{r}$ is the ratio of the refresh rate to the update rate. Thus, if the continuous image is moving at a constant velocity $\underline{v}$, the displacement of the display image will be in accord

with a velocity of zero for $\underline{r} - 1$ and a velocity of $\underline{rv}$ for one out of every $\underline{r}$ periods.

Our research indicates that the perceptual consequences of such images vary with a number of interdependent factors, including the duration of the motion sequence and the velocity of the target. In general, however, the target is seen in "jerky" motion only when the motion sequence is very short or when the observer attempts to maintain a steady fixation. When the observer is encouraged to track the target and given time to do so, the velocity of the eyes approximates that of the continuous image (i.e., $\underline{v}$). The resulting spatial percept corresponds to the spatial form that would be repetitively "painted" on the retina if the pursuit velocity were precisely $\underline{v}$. This form appears to move at a constant velocity, although it may also be characterized by flicker or internal movement.

Figure 1c illustrates the spectrum of the display image that would result if the image specified for Figure 1a were sampled at 30 Hz and displayed at 60 Hz (i.e., $\underline{r} = 2$). Note that the region of support of this spectrum consists of lines at multiples of the sampling rate. Although these lines all have a slope of $-1/\underline{v}$, they do not all have the same spatial spectrum. The spectrum of the constant velocity line is replicated at even-numbered multiples of the sampling rate (i.e., at multiples of the display rate), whereas a different spectrum is replicated at odd numbered multiples of the sampling rate. Neither spatial spectrum matches that in Figures 1a and 1b. In particular, the spatial form defined by the constant velocity line in Figure 1c is not a single vertical bar. Rather, as demonstrated by inverse Fourier transforms of such spectra, it is the form that would be perceived during smooth pursuit eye movements.

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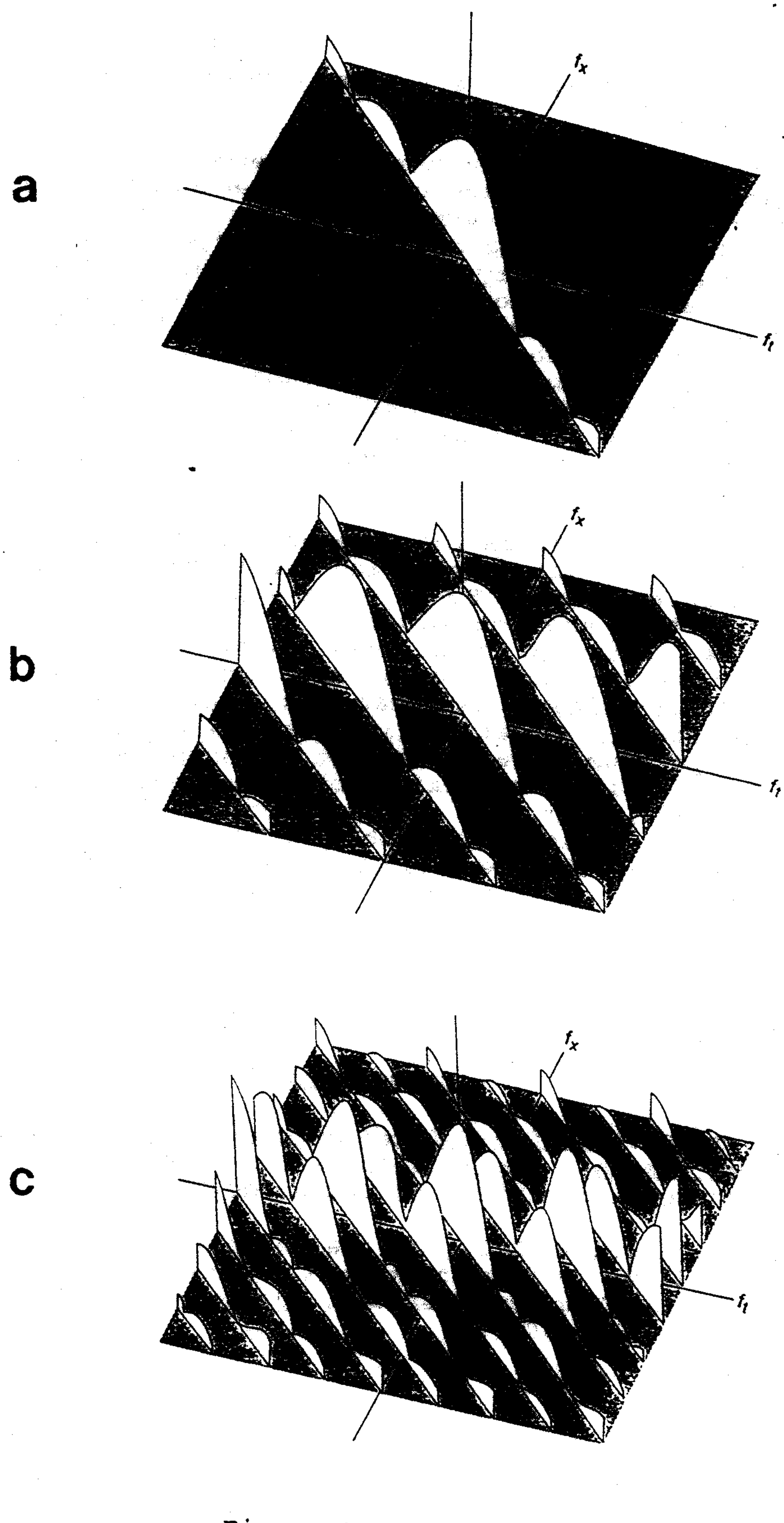

Figure 1. Image Spectra

Infrared Imagery in Flight

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With the aid of advanced imaging sensors, pilots of both rotorcraft and fixed-wing aircraft can now conduct missions that were not possible just a few years ago. In general, these sensors can be viewed as extensions to a pilot's own visual system. They allow the pilot to safely fly and complete missions at times when environmental conditions (e.g., darkness, dust, smoke) would preclude flight or mission completion with unaided vision. One class of imaging sensors that has been used extensively by pilots for targeting, navigation, and flight control purposes are thermal imaging (infrared imagery) systems. In general, thermal imaging sensors are sensitive to thermal radiation in the infrared range of the electromagnetic spectrum (3-5 microns or 8-14 microns). (Visible light, to which the human eye is sensitive, is in the range of 0.4 to 0.7 microns.)

A thermal sensor creates a visual scene on a cathode-ray tube (CRT) that can be mounted either on the cockpit panel or the pilot's helmet. The visual scene provided by the sensor is monochrome and <u>appears</u> to be similar to black and white television (TV) or reversed-video (i.e., phase inverted) black and white TV. However, despite the overall appearance of similarity to TV images, there are important differences. An important qualitative difference between thermal imagery (TI) and TV or unaided vision occurs as a direct result of the image's source: The distribution of gray shades in TI represents relative temperature differences, rather than brightness and reflectance differences. Compared to TV images or directly-viewed visual scenes, TI has the following properties: (1) Heat-emitting objects generally have higher contrast with the background; (2) Shadowing/shading information may be absent; (3) Sensor polarity settings (i.e., the assignment of white or black to hot) may lead to perceptual errors; and (4) A given object may appear quite different when viewed under different environmental conditions (e.g., time of day, yearly season, humidity, ambient temperature). These characteristics of thermal imagery directly impact flight control and navigation, particularly at very low altitudes: (1) Pilot workload is generally higher (Hart & Brickner, 1989); (2) Object distances may be inaccurately estimated (Hart & Brickner, 1989), (Hale & Piccione, 1989); (3) The horizon line may be indistinct (Bohm, 1985); and (4) Specific objects in the environment may change luminance levels drastically as a function of time of day (Berry, Dyer, Park, Sellers & Telton, 1984).

A variety of studies have been completed at the NASA Ames Research Center over the past few years investigating pilots' ability to use infrared imagery for flight navigation, orientation and flight control. The following is a brief description of a few of those studies.

Infrared Imagery Interpretation (Expt. 1)

An experiment by Brickner and Staveland (1989) investigated people's ability to recognize identical targets using TV or TI imagery recorded simultaneously during helicopter flights. By comparing these two imagery conditions, they attempted to determine the underlying visual and cognitive processes that humans use when viewing images derived from reflected visible light (TV or direct vision) or emitted thermal radiation (TI). Targets included navigational features, such as rivers and canyons, as well as more "traditional" targets such as vehicles and runways. TV and TI imagery were recorded simultaneously during two helicopter flights. Flight tapes were edited into 21 dynamic segments each of which contained a specific target. Subjects viewed only one type of sensor imagery (TV or TI) on a given trial. Prior to each trial, the experimenter told the subject which target was to be located and recognized on that trial. Time to identify a target, measured from the point at which it first became visible on the screen, was recorded. The results showed that for natural targets (e.g., river, canyon) recognition time for TV images was faster than when the identical targets were viewed using TI. Conversely, man-made targets (e.g., road, tower) were recognized more quickly with TI than TV. The results were interpreted as suggesting that, for natural targets, TI representations did not correspond to the subjects' expectation or cognitive prototypes (Posner & Keele, 1968). That is, for natural targets, the TV targets looked as the subjects expected but the TI targets did not.

Infrared Imagery Interpretation (Expt. 2)

A follow-up study was conducted by Foyle, Brickner, Staveland and Sanford (1990) using the same general experimental procedure as above but with more test items. In order to expand upon the results of Brickner and Staveland (1989), three categories of targets were defined: (1) Naturally-occurring terrain features; (2) Stationary non-terrain targets; and, (3) Moving non-terrain targets. As discussed above, Brickner and Staveland (1989) found that target recognition was faster for man-made targets with TI than with TV. The reverse was true for natural (terrain-type) targets: TV yielded faster recognition times than did TI. The results of this study replicated those findings. Type of target strongly influenced recognition time. For both categories of non-terrain targets, recognition times with TI were faster than when those targets were viewed with TV. The opposite held for terrain features, with TV yielding much faster recognition times (this can be seen subjectively in Figure 1). As explained by Brickner and Staveland (1989), this may have occurred as a result of a mismatch between the cognitive mental prototype (the expected appearance of the target) and the target's actual appearance on the TI display. For terrain features, targets viewed with TV may have matched more closely the subject's mental prototype than did targets viewed with TI.

Results from a display parameter analysis supported the hypothesis that performance with TI terrain targets was influenced more strongly by cognitive factors (e.g., mental prototype, expectation) than was performance with TV terrain targets. In order to determine the relationship between display

parameters and recognition times, a multiple regression analysis was completed in which target display parameters (area, contrast, histogram standard deviation, and luminance) were statistically combined to predict recognition times. For non-terrain targets, there was a moderate and statistically significant correlation. For terrain targets, the correlation was much smaller and nonsignificant. That is, display parameters predict recognition times for non-terrain targets, but not for terrain targets. This suggests that recognition of non-terrain targets depends on display parameters, while recognition of terrain targets depends more on cognitive processes.

Biederman (1985) proposed a two-stage model of object identification. The first stage is a lower-level, input-driven process in which edges and primitive form features are extracted. The second stage is a higher-level cognitive process in which these object components are matched to the internal mental representation of objects. Objects are identified when the match is a good one. Biederman argues that facilitation or delay of lower-level processes should have a direct effect on the overall identification latency. Interpreting the results of the present study in terms of this model, recognition time was affected by the lower-level processes (as evidenced by a significant correlation with the four display parameters measured) for non-terrain targets. Recognition times for terrain targets should have been predictable from the display parameters as well. However they were not. An explanation for this failure could be found in the second stage of Biederman's model: With terrain targets, there was a failure of the displayed targets to match the subject's mental representations. These data and analyses lend support to the hypothesis that the recognition of non-terrain targets depends on the characteristics of the human visual system and image display parameters. In contrast, recognition of terrain targets may be determined by some other mechanism, which is presumably, cognitive.

Related Research

In addition to the above work on interpreting infrared imagery, other on-going research issues relevant to the use of sensor systems in flight include: Distance estimation with infrared imagery and night-vision goggles (Foyle & Kaiser, 1991; Kaiser & Foyle, 1991); Flight performance as a function of sensor field of view (Brickner & Foyle, 1990); and, Attentional issues in head-up displays (HUD) and superimposed symbology (Foyle, Sanford & McCann, 1991).

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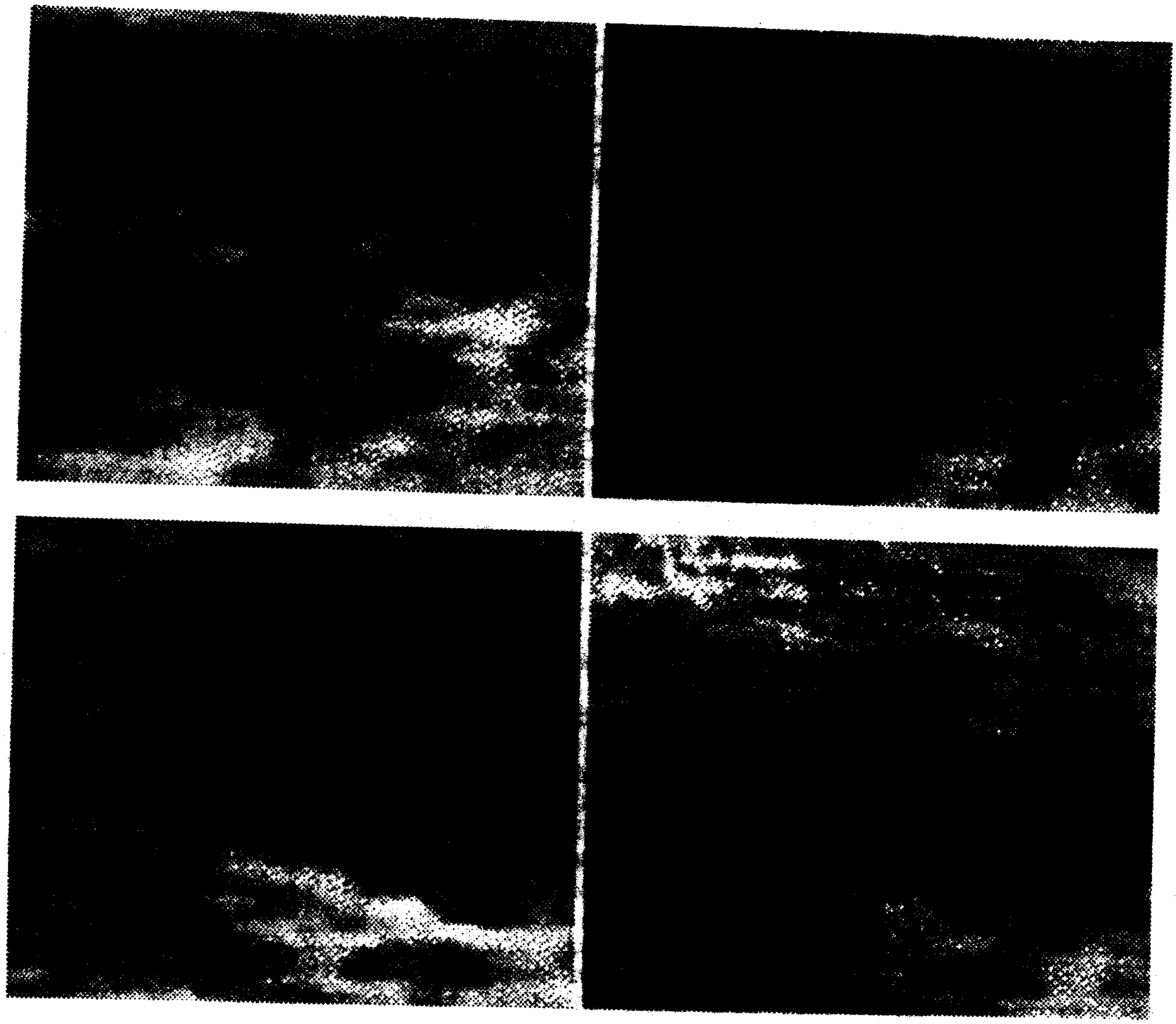

Figure 1. Sample objects recognized by subjects. Infrared imagery is shown in the left panels and television imagery on the right. Top panels show a fence post (non-terrain target) and bottom panels show a group of trees (terrain targets).

Night Flights Over Featureless Terrains: The Use of Cueing Lights

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Abstract

Night vision devices do not provide sufficient information for safe helicopter control in certain environments, such as the desert or water. During Operation Desert Shield/Desert Storm, the U.S. Army proposed that it may be possible to augment the available information by projecting a pattern of lights onto the ground forward of the aircraft. Presumably, the dynamic patterns formed by the cueing lights could provide sufficient information for obstacle detection, or perhaps even could serve as a pseudo-flight director. We have tested the effectiveness of three such configurations under two levels of ambient illumination in an active flight-control task.

Five experienced general aviation pilots served as subjects. Their task was to maintain a "safe altitude" while flying 30 simulated flights over a wireframe grid terrain containing a level segment, followed by an uphill or downhill slope. Overall, the results indicate that certain cueing-light configurations can be used effectively as pseudo-flight directors without impairing the pilot's use of available natural cues in the scene. Pilot errors (indexed by the duration of ground contact) were reduced for all three light configurations compared to performance expected in total darkness. Under twilight lighting (dim terrain), however, only two configurations produced flight performance comparable to a control condition. A second performance measure consisted of the computation of flight-path profiles based on time-sampling the craft's altitude throughout the simulated flight. When these profiles were compared, the same two configurations again proved to be equally effective as aids in altitude control.

As operational requirements increase the need for helicopter pilots to fly under low-visibility conditions, so too does the need for aids to insure the safety of these missions. Our results indicate that certain relatively low cost solutions can be used effectively to augment the information available in a limited-feature terrain. Future research on the use of cueing-light configurations should consider issues related to their successful implementation, including field calibration and pitch stabilization.

AN IDEALIZED EXAMPLE OF TRAINING SYSTEM DEFINITION FOR A NAVY VISUAL SIMULATOR

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The quality of military training systems depends on the methodology applied to developing the system concepts and defining technical performance requirements. An orderly, fact-based process of translating training requirements to visual simulation performance requirements is described in the following example. The example was selected because it appears to have been more successful than most in arriving at an early definition of a training simulation system which fully met user needs when delivered. The concept development process began with the identification of visual tasks to be trained and led to a preliminary specification with quantified performance requirements for the visual simulation system.

Key ingredients of the method are the use of a multi-discipline team and integration of the information by the team into a cohesive set of guidelines for use by the system program office in developing the system. The project team members backgrounds included research, engineering, human performance and training. A research simulator was used to perform experiments to answer specific questions which were critical to the program.

The methodology described is very pragmatic in trying to establish reasonable confidence in the preliminary system design without attempting to resolve every conceivable question. It was also forced to meet stringent budget and schedule constraints. The example system has been built and validated for the intended training application.

AN OVERVIEW OF VISION RESEARCH AT THE FAA CIVIL AEROMEDICAL INSTITUTE

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Paper to be Presented
at the
Interagency Technical Information Exchange,
Armstrong Laboratory, Williams AFB, AZ
1-3 October 1991

AN OVERVIEW OF VISION RESEARCH AT THE FAA CIVIL AEROMEDICAL INSTITUTE (CAMI)

A. Aviation Physiology Laboratory

Vision research in the Aviation Physiology Laboratory, Aeromedical Research Division, CAMI, has focused recently on clinical concerns and aeromedical standards review. Active research is ongoing in both the Neuroscience and the Vision Research Sections. In the Vision Research Section, the following research activities are recently completed or current.

I. The Effect of Simulated Altitude on the Visual Field of Glaucoma Patients and the Elderly.

Glaucoma is a condition in which an increase in intraocular pressure occurs that is sufficient to cause degradation of the optic disk and defects in the visual field. Pilots with glaucoma may present special problems since they may present acceptable visual field results at ground level, but experience changes in visual field with exposure to altitude hypoxia. Repeated exposure to high altitudes may accelerate the progression of glaucoma in passengers as well as pilots. If a temporary increase in field loss at typical flight altitudes could be demonstrated, this would represent a stress of the visual system that might cause a permanent increase in visual field loss.

A collaborative research study with faculty members from the Northeastern State University, College of Optometry, was performed to assess whether glaucoma and elderly subjects at an atmospheric pressure simulating the high altitude end of the typical flight environment (i.e., 10,000 feet) will suffer temporary scotomas compared with their fields at ground level.

Visual fields were tested with the 24-2 threshold program on the model 630 Humphrey Field Analyzer. This program estimates the retinal threshold at points within the central 24 degrees of the field of vision. Subjects were exposed to approximately 24 minutes of altitude prior to the initiation of the visual field test, which took approximately 8 minutes. Six glaucoma, 12 age-matched normal, and 6 younger subjects were tested.

Our results indicated that at a simulated altitude of 10,000 feet no effect on any of the visual fields was measured. We concluded that there was no evidence to suggest a change in the present FAA standards allowing certificates to persons with glaucoma, nor was there any evidence that should discourage glaucoma patients from flying as passengers.

II. The Use of Contact Lenses in the Civil Airman Population.

Federal Aviation Regulations permit the routine use of contact lenses by civilian pilots to satisfy the distant visual acuity requirements for obtaining medical certificates. In order to guide future medical certification decisions, policy changes and airmen education safety programs, an epidemiologic study was performed of active airmen who wore contact lenses over a 20-year period (1967-87).

The percentage of airmen with distant vision restrictions increased by 1.4X during the study period. Percentage of airmen with defective distant vision increased fastest in first-class airmen, about 2.0X faster than either 2nd-or 3rd-class.

The percentage of airmen with contact lenses increased by 4.0X during the study period. The prevalence rate with contact lenses increased fastest in first-class airmen, about 4X faster than either 2nd- or 3rd-class.

We concluded that contact lens use in civil airmen has increased dramatically, but at a much faster rate in first-class medical certificate holders.

III. Aphakia and Artificial Lens Implants in the Civil Airman Population.

The FAA allows civil airmen with aphakia to fly with waivered certificates. Airmen with aphakia and artificial lens implants have been associated with higher accident rates when compared to the total airman population in two prior FAA studies. Additionally, elderly pilots are comprising a larger percentage of the total civil airman population.

Our current study looks at civil airmen with aphakia and intraocular lens (IOL) and their association to aviation accidents from 1982-85. Accident analysis is being completed. The prevalence for both aphakia and IOL airmen increased most for bilateral and second class certificate holders; the prevalence of aphakia increased most for males and the rate for IOL increased most for females during the study period. The incidence surprisingly declined in both pathology categories during the later years of the study period. Factors that could contribute to these unexpected findings include:

1) Self-selection (voluntary removal) from flight status by airmen with cataract and early post-operative aphakia;
2) Reluctance of airmen with cataract to have their pathology corrected with surgery;
3) Incompatibility of modes of correction or complications of surgical procedures with certain flight operations;
4) Vision disability from aphakia and IOL; and
5) More stringent FAA disqualification criteria being initiated during the study period.

A second study on these aphakic and IOL airmen is being planned to further evaluate these trends of use.

IV. Glare Vision Testing in the Certification of Pilots.

The use of glare testing for the medical certification of pilot applicants has been recommended by several independent sources, including the American Medical Association and the National Academy of Sciences' Institute of Medicine. The FAA has certified with medical waivers airmen with different ophthalmic conditions and ophthalmic devices, which have been associated with increased glare sensitivity. The applicability of glare testing to aviation has not been established.

The major objectives of this project are to:

1. Identify the effect of glare on vision performance under simulated flight conditions in selected visually compromised (e.g., aged, cataract, aphakia, IOL) and ophthalmologically normal test subjects.
2. Assess current airman vision standards and certification policy concerning these airmen;
3. Recommend medical standards changes for these vision pathology categories; and
4. Revise educational programs and develop aeromedical related pamphlets for flight crew personnel.

An evaluation of commercial glare test devices is being completed. An evaluation of cockpit factors that may increase glare sensitivity is being performed with the assistance of a contract with a university-based group.

For further information on these research topics, please contact Van B. Nakagawara, O.D., FAA-CAMI, P.O. Box 25082, AAM-620, Oklahoma City, OK 73125, Phone: 405/680-4875.

V. Visual Scanning Behavior.

An air traffic controller in front of a sector suite display must be continuously aware of events occurring within a large visual space. As the workload increases (the number of events, rate of occurrence), the controller's task becomes increasingly difficult. There is a general tendency in these conditions to concentrate, or "lock" onto, some subset of the events, largely or completely ignoring any other displayed information. Our research is investigating some of the display-oriented factors which may influence this "locking" tendency. The results to date suggest that factors such as workload differences and spacing between display areas are not very important. We are currently investigating the effects of assigning different values to displayed events. We anticipate that during high workloads, the subjects will tend to lock onto the higher valued event.

One limit of our present system is that the on-screen events are stationary. That is, they involve reading symbols occurring within limited and predictable locations on the display. In reality, the task of the air traffic controller is mostly concerned with evaluating complex patterns of aircraft movement on their displays. We are planning to implement tests in which the subject evaluates patterns of movement on the display. For example, are any of the moving symbols on screen about to collide? If so, which ones? Where will the collision occur? If more than 2 symbols will collide, which will collide first? As in our previous research, the experimental design will attempt to define some of the factors controlling attention locking.

For further information on this research, please contact Alvin M. Revzin, Ph.D., FAA-CAMI, P.O. Box 25082, AAM-623, Oklahoma City, OK 73125, Phone: 405/680-4875.

B. Human Factors Research Laboratory

Two current vision research projects of the Human Factors Research Laboratory, Human Resources Research Division, CAMI are described below.

VI. Gaze Measures as Predictors of Delayed Responses or Missed Signals in an ATC Simulated Display.

This research project was developed as an outcome of the US/USSR Agreement on Cooperation in Transportation Science and Technology and involves collaboration with Dr. Nikolai Stoliarov from the USSR Scientific Experimental Center for ATC Automation, Moscow, and Dr. John Stern from Washington University Behavior Research Laboratory, St. Louis.

Air Traffic Control Specialist (ATCS) performance is highly dependent on the ability to maintain visual scanning of a radar scope and flight progress strips while processing auditory and visual input, planning, decision-making, and providing verbal instructions. With increased automation entering into aviation environments, it will become increasingly important for operators to maintain vigilance and attention under circumstances in which they are less involved in active control and function more as system monitors. A better understanding of the conditions associated with loss of attention or vigilance in those environments, or in simulations of those environments, will serve as the basis for developing more effective error prevention techniques and procedures.

Previous research suggests that visual gaze measures may be predictive of occasions when operators are less efficient in the acquisition and processing of visual information. These techniques have been applied to assessing scanning behavior in novice and experienced helicopter pilots (Stern and Bynum, 1970) and have demonstrated a significant relationship with aspects of the performance of pilots during simulator flights (Morris, 1984).

This project will determine the validity of the hypothesis that gaze measures can be used to identify and predict missed critical events, or delayed detection of critical events on an ATC monitoring task, and that individual differences in vigilance performance are related to gaze and eye-blink measures.

Data collection for this study is currently being performed at CAMI, using an ATC simulation task. The subject population includes only college students at present. Subject performance on an ATC simulation monitoring task is being assessed in three sessions on three successive days. Each session involves 2 hours of continuous complex monitoring performance. Subjects are asked to detect (a) altitude indicator dysfunctions, (b) when two aircraft are at the same altitude on the same flight path, and (c) the appearance of targets that represent VFR aircraft. Recordings of gaze measures and task performance are made continuously during the experimental sessions. Gaze measures include: (i) aspects of saccadic eye movements (amplitude and duration); (ii) information concerning fixation pause duration; (iii) eye blink (timing, amplitude, and closure measures); and (iv) head movements not associated with making of a motor response. The gaze measures and performance measures will be compared statistically.

The data obtained from this study will contribute to a better understanding of the conditions associated with loss of attention or vigilance in complex monitoring.

VII. Evaluation of Functional Color Vision Requirements and Job-Related Selection Tests for Aviation Occupations.

The final vision project to be described is being conducted in the Workload and Performance Section.

Concerns have been expressed from the Equal Employment Opportunity area that FAA color vision standards may be too strict for the present and future ATCS tasks, and that color vision tests are not validated for ATCS. The objectives of the present project are: (1) to evaluate and validate the color vision standard and clinical color vision selection tests for ATCSs in current terminal, center, and flight service station facilities, (2) to develop practical color vision tests for use in selection of ATCSs for the current work environment, and (3) to evaluate color vision requirements and appropriate selection testing for the next generation of ATC workstations, and advanced weather information systems for ATC and Flight Service Station (FSS).

In the present ATC and FSS environments, job analysis and field studies of job functions identified important tasks that involve color as a primary, non-redundant cue. Those tasks are: (1) distinguishing between red and black printing and handwriting on flight progress strips at en route centers; (2) identifying aircraft location and orientation by red, green, and white aircraft position lights in night tower operations; and (3) identifying at FSS facilities weather radar colors that represent different precipitation levels.

An experiment was conducted to evaluate the relation of type and degree of color vision deficiency and aeromedical clinical color vision screening test scores to performance in simulations that included the above three ATCS color tasks involving non-redundant color coding. The subjects included 121 normal trichromats and 123 subjects with varying type and degree of color vision deficiency as classified with the Nagel anomaloscope. Errors were rare among normal trichromats. Error frequency in the simulated ATC tasks increased with degree of color vision deficiency. The aeromedical clinical color vision tests had acceptable miss rates, but a few tests had high false alarm rates. Practical color vision tests have been developed for the flight progress strips and aviation lights tasks that are related to en route center and tower situations, respectively. Those tests involve reproductions of actual flight progress strips and actual lights that meet specifications for aviation-red, -green, and -white. An appropriate simulation method for a practical color vision test pertaining to color weather radar is currently being pursued.

The next phase of this project will involve evaluation of color vision requirements and appropriate job-related color vision test methods for displays of the Advanced Automation System Sector Suite, a new workstation for ATC, and for displays of NEXRAD and other developing systems.

For further information on Human Resources Research Division vision projects, please contact David Schroeder, Ph.D., FAA-CAMI, P.O. Box 25082, AAM-500, Oklahoma City, OK 73125, Phone: 405/680-4846.

Vision Research at NASA Ames FLM Branch

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Vision is a critically important component of many NASA missions. It is the main communication channel in a wide range of man-machine interactions. The Vision Group of the Human Interface Research Branch at NASA Ames is involved in research into many aspects of visual information processing. A common goal of this research is to understand how the human visual system processes visual information and to apply that knowledge to the design of systems which will be more efficient and safer for the human operator. With respect to training and real time simulation, our research can be divided into two main areas:

1. Digital Image Processing.

An integral part of many simulation systems is the visual display or visual scene attachment. Through the use of computer graphics techniques, digital imagery is generated to simulate out-the-window scenes. Many algorithms and ideas from the field of digital image processing are incorporated into the design of these displays and have an impact on the the realism and effectiveness of the imagery. The Vision Group is currently involved in research on a range of topics in the area of digital image processing and transmission:

-Perceptual Components Architecture for Digital Imagery
-Pyramid Image Codes
-Self-Calibrating Networks for Image Reconstruction
-Computational Vision: Color Perception

-Exploiting Perceptual Transparency in Avionics Displays
-Visual Display Modeling and Evaluation
-Image Halftoning
-Image Fusion

2. Motion Processing in Man and Machine.

A large portion of the research of the Vision Group involves understanding how the human visual system processes motion. Motion is important in any activity that involves movement of oneself or a craft through the environment and hence is an integral part of flight control and simulation. Understanding how humans use visual motion information in these tasks helps in all areas where the human is in the loop and has an impact on many areas of human factors engineering.

Our research on motion can itself be divided into two areas: The first deals with trying to understand how the visual system processes the two-dimensional motion that occurs on the retina. Historically, the emphasis of the group has been on the development of computational models of motion processing but there is also a strong psychophysical experimental program underway to test and refine these models. One of the first pioneering efforts to model human 2-D motion processing through the use of spatio-temporal filters, was carried out by members of the Vision Group (Dr A. Watson and Dr A. Ahumada). Several algorithms have also been developed within the group for the estimation of two-dimensional image velocity fields from image sequences.

The second main area of motion research deals with the 3-dimensional motion problem; namely how does the visual system use the 2-D motion information it has acquired to derive information about the 3-D environment such as heading direction, rotation rates and surface layout? We have developed several models in this area and have an ongoing research program testing human performance in 3-D self-motion estimation. This research has important applications in the areas of robotics, obstacle avoidance, autonomous vehicles and nap-of-earth rotorcraft flight, and will also provide insights into the motion information required by pilots for flight control.

Selected Publications:

Ahumada, A.J. Jr., & Mulligan, J.B. (1990). Learning receptor positions from imperfectly known motions. *SPIE Vol 1249. Human Vision and Electronic Imaging: Models, Methods, and Applications.*

Heeger, D. J., & Jepson, A. D. (1990). Visual Perception of 3D motion. *Neural Computation*, 2, 129-137.

Perrone, J.A. (In Press). A model for the computation of self-motion in biological systems. *Journal of the Optical Society of America, A.*

Stone, L.S., Watson, A.B. & Mulligan, J.B. (1990). Effect of contrast on the perceived direction of a moving plaid. *Vision Research*, 30(7), 1049-1067.

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ONGOING R&D IN NIGHT VISION DEVICES

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(Summary not available)

Visual Limitations of NVDs

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Introduction

Is there a 'bridge' to the existing vision literature for night vision devices (NVDs)? If such a 'bridge' can be determined, it may be possible to 'translate' the vast vision literature and predict many of the effects of NVD on visual performance. For example, if NVD behavior can be modeled by known optical devices, then studies of optical blur would be directly applicable to NVDs. If, however, NVDs are fundamentally different from purely optical devices such modeling may be impossible -- a 'bridge' may not exist.

The fundamental description of a signal processing device's ability to pass information is the ratio between the signal going into the device and its output. The collection of these ratios over the frequency range of interest is called the modulation transfer function (MTF). While the MTF of conventional optical systems may have different intercepts and rate of change, they all have similarly shaped MTFs. Thus, if NVDs are to be easily modeled by conventional optical systems, their MTF's shape must be similar to that found with conventional optics.

There are two fundamentally different ways of determining MTF. The first is the physical measurement of input and output signals. The physical measurement can be done several different ways. One method involves measuring the contrast of a two-dimensional sinusoidal grating at different spatial

frequencies. Another method presents a single sharp line and measures the amount of spread by the NVD, which is then mathematically transformed with Fourier Analysis into a MTF. It is important to note that the human visual system is not involved in these physical determinations and therefore any possible interaction with the visual system will not be found. The other fundamental approach is to psychophysically determine MTF. This method was pioneered by Campbell and Green in 1965 for the human eye. The minimum amount of contrast required for subjects to just detect a two-dimensional sinusoidal grating is determined with and without the optical device processing the signal. (The reciprocal of these curves are contrast sensitivity functions.) The amount of additional contrast required to detect the target with the device is equal to the amount that the signal has been demodulated by the device. Thus, the ratio between the contrast required with the device and the contrast required without the device is the modulation transfer ratio. The test is repeated for each spatial frequency of interest and the MTF determined.

Method

The NVDs tested were two pair of new ANVIS 6s. These devices use third generation imaging tubes and are currently in use by operational forces. The subjects were two male aviation students awaiting flight training; they were physically qualified for flight and had uncorrected visual acuity of at least 20/20 in each eye. The measurements were made with an Nicolet Optronics 2000 contrast sensitivity tester. This instrument has been modified with a kit developed by the U.S. Air Force (generously provided by Col Melvin O'Neil) to allow two-interval forced-choice testing procedures. The luminance reaching the eye was adjusted with Kodak neutral density filters (filter factor of 1.3) so that it was perceptually equal with and without the NVD. The input to the goggles was also reduced with Kodak neutral density filters (filter factor of 3.0) to allow the stimulus to be viewed through the goggles at its standard luminance. The two interval forced choice procedure was utilized with a 3 down/1 up staircase. A total of six reversals per run were collected with the last four reversals utilized for threshold determination. Each of the spatial frequencies (0.5, 1.25, 3.0, 4.5, 6.0, 12.0, and 18.0 cycles per degree) were tested three times per condition (unaided, NVD A, and NVD B) for each of the two subjects. All data for one spatial frequency were collected before proceeding to the next spatial frequency. The order of the spatial frequencies, subjects, and conditions were all counterbalanced.

Results

The unaided contrast threshold results are presented in Figure 1, in the more readily recognized contrast sensitivity form. The contrast sensitivity (equal to 1/threshold contrast) is plotted on the logarithmic y axis, as a function

of spatial frequency on the logarithmic x axis. The error bars are equal to ± one standard error. These results are consistent with the literature, with sensitivity peaking between 3 and 4 cycles per degree and falling off at both higher and lower spatial frequencies. The small error bars and smooth flow of data points indicate a good level of subject training resulting in consistent results and a lack of order effects.

In Figure 2, contrast thresholds obtained with the two ANVIS 6s have been added. Again the classic inverted 'U' function is evident, with small error bars, good consistency between the two goggles, and a lack of order effects. Note that at every frequency tested (from 0.5 through 18 cycles per degree) visual performance with the goggles was reduced. From 3.0 cycles per degree and higher the visual performance was reduced by approximately one order of magnitude. Thus, visual performance is not only limited by the known reduction in best visual acuity (a factor of 2 from 20/20 to 20/40, or 0.3 orders of magnitude), but is dramatically limited by reduced contrast sensitivity across a very wide range of vision.

The MTFs for both ANVIS 6 goggles tested are shown in Figure 3. The ratio between the threshold contrast with the NVD and without the NVD is plotted on the logarithmic y axis as a function of spatial frequency plotted on the logarithmic x axis. The error bars are ± one standard error of the mean and are relatively small. The results of the two tested goggles are essentially the same. Again, there is a lack of order effects demonstrated by the smooth flow of the interleaved data points. The shape of the functions is totally unexpected. The shape of a 'normal' optical systems MTF is expected to be monotonic anchoring at 1 for extremely low (i.e., fat bars) spatial frequencies and falling smoothly to a cutoff spatial frequency. Neither pair of goggles demonstrated this shape. The performance does not steadily decrease to the cutoff spatial frequency of approximately 15 cycles per degree. Instead a plateau of performance is evident for spatial frequencies of 3.0 cycles per degree and higher. The MTFs of the goggles are clearly inconsistent with MTFs of 'normal' optical systems.

Discussion

If an individual's expectations of visual performance are determined by the brightness of the scene, then the visual performance experienced with NVDs will be significantly worse than expected. Interestingly, these expectations of performance may not be conscious, but rather may function at an automatic level. If the automatic expectation is to see, unexpected failure to see can have catastrophic results. Interestingly, the individual who suffers from these results could be totally unable to identify the source of the problem.

Is it reasonable to expect the laws of optics dealing with continuous images to apply to electronics and discontinuous (i.e., discretely sampled) optical images? In hindsight, the more surprising finding would have been if these complex electroptical devices really did visually function as simple lenses.

Conclusions

1) NVD use resulted in vastly reduced visual performance at all spatial frequencies tested when compared to what our unaided experience would predict at similar luminance levels.

2) NVDs are fundamentally different than purely optical devices.

3) Current knowledge of the effects of optical devices on visual performance have fundamentally limited applicability to NVDs.

4) Understanding the causes of these differences and their effects on performance is required to predict NVD effects on visual performance, flight effectivity, and ultimately mission accomplishment.

Acknowledgements

This study was conducted at NAMRL by 2nd LT Huckabone while awaiting flight training.

Special thanks are due to Ens Paul Laube, USN, for serving as a subject in this study while awaiting flight training.

This project was funded under NMRDC work unit 63706N M0096.002.

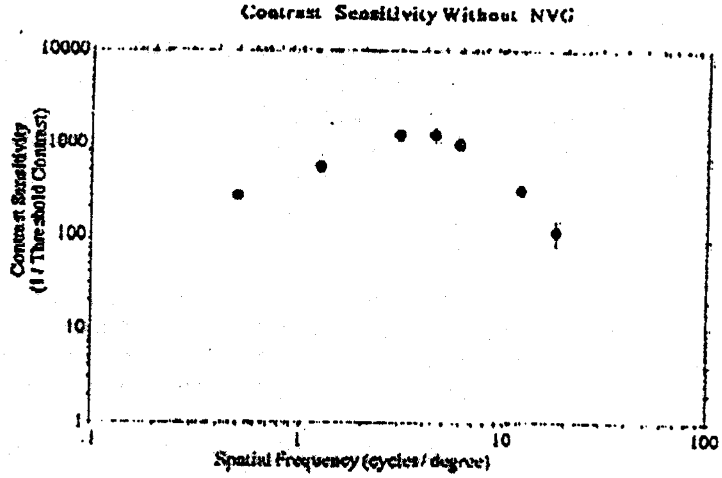

Figure 1.

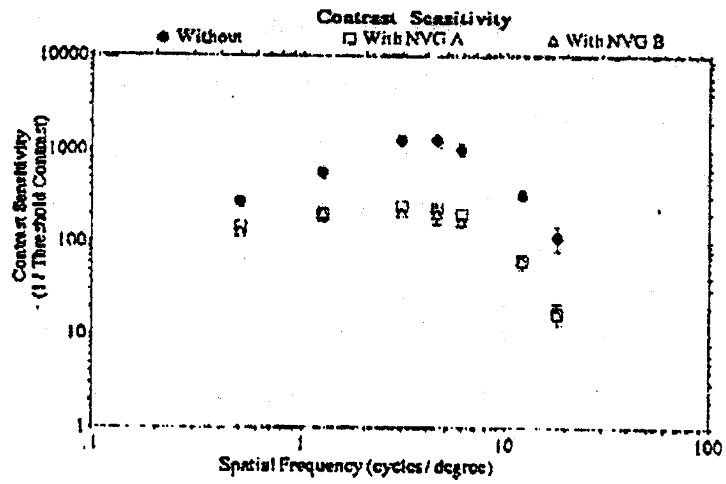

Figure 2.

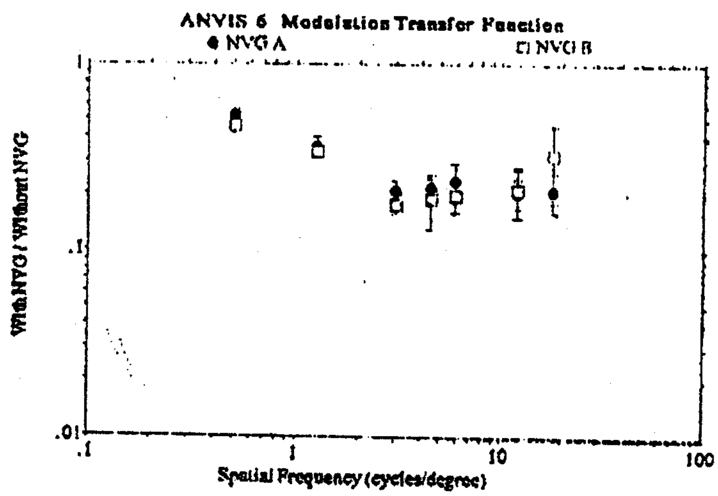

Figure 3.

Diopter Blur

Aided Night Vision Training Kit

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Operation Desert Storm taught us many important lessons concerning the training and ultimate use of Night Vision Devices in the operational environment. One important lesson learned concerning Night Vision Goggle (NVG) training is that maximum time training with the goggles actually in use is very important. Therefore, obtaining maximum goggle time while training is a prime objective of new training methods.

The Naval Aerospace Medical Institute and the Naval Aerospace Medical Research Laboratory has developed a portable, inexpensive Aided Night Vision Training Kit. This kit in no way replaces the training received in night vision labs such as those at MAWTS-1, but augments previously received training. The kit is designed to be utilized with Night Vision Goggles and optimize the amount of time actually spent on goggles.

The training covers the mechanics of how goggles work, including a more in-depth description of microchannel plate technology to help gain a better understanding of how the goggles work. Descriptions of different types of goggles, specific performance characteristics as they pertain to these goggles and the effects of different environment conditions on the goggles are also covered in the kit. A great deal of narrative as well as diagrammatic information on the proper methods of goggle adjustment is included in the latter part of the presentation. The final portion of the kit includes several very important demonstrations including the effects of decreased illumination on the goggles, the effects of incompatible lighting on the automatic brightness control and the effects of strobe lights and lasers on the goggles.

The slides are all black and white, with the exception of the incompatible lighting demonstration, projected through a Kodalith film laminated with Kodak Wratten neutral density filters. Utilizing black and white narrative slides in place of kodachrome color slides eliminates any adverse affects which the neutral density filters may have upon chromaticity transmission. The kit is totally portable and designed to be co-located with squadrons having easy access to NVG's. The kit will be exported along with the necessary projector blimp (cover) when necessary. The only requirements for the training are NVG's, a dark room, a Carousel projector and the necessary projector blimp.

NIGHT VISION DEVICE TRAINING RESEARCH at WILLIAMS AFB, AZ

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BACKGROUND

Night vision devices (NVD) in various forms have been used in the Air Force fixed and rotor wing aircraft for more than ten years. The common denominator spanning all weapon systems and mission objectives is the interface between a helmet-mounted visual display and the human operator. A unified training program which introduces experienced aircrew members to an NVD environment will form a solid foundation necessary to effectively employ such visual devices.

During the past year, the Aircrew Training Research Division of Armstrong Laboratory has focused on developing and evaluating an Initial NVD Training program. During FY92 this program will transition to Kirtland AFB, NM, for operational evaluation with the 1550th Combat Crew Training Wing. One aspect of this training program of interest to applied vision researchers are the NVD Test Lane.

Other aspects of the NVD Training Research program at Williams include NVD visual task performance and advanced NVD simulation techniques. The major thrust of all of these efforts is to investigate cost-effective ground-based training techniques which adequately prepare air crews to deal with the visual limitations imposed by unique visual systems.

NVD TEST LANE

The term "NVD Test Lane" refers to a set of standardized procedures, an NVD Resolution Chart consisting of high resolution square wave grating patterns, and a standardized light source. This provides crew members the ability to adjust their NVGs to obtain the best visual acuity possible for the goggle in use at the time. Field data indicates only about 30% of current NVG users are able to adjust their goggles to achieve the best visual acuity possible.

The basis of the Test Lane is a measure of visual acuity using a resolution task to determine the minimum distance between objects for the discrimination of separateness. While visual acuity is not the only measurement which could be taken (e.g., contrast sensitivity), it is an expedient method to provide a controlled setting for aircrew members to perform their adjustment procedures and to assess the function of the device itself. With a known target (the Resolution Chart),

controlled lighting, and standardized procedures, the crewmember has the ability to tell if the devices is adjusted properly and performing up to design specifications.

NVG TASK PERFORMANCE

The ability of aircrew members to perform some visual tasks (such as distance estimation) can be severely compromised during NVG flight. The development of effective ground-based training procedures for these tasks will allow aircrew members to rehearse difficult scenarios. Preliminary plans are currently under way to obtain performance data under simulated condition, in-flight, and in the field. To support this study, the database used for previous visual systems evaluation studies is being modified for use with night vision goggles. Once complete, this database will allow comparison studies between daytime performance with full visuals, daytime performance with restricted field of view, nighttime performance with NVG aided vision. This NVG task performance measure can then be used in an evaluation of the effectiveness of some of the advance NVD simulation techniques.

ADVANCED NVD SIMULATION

One challenging aspect of NVD aircrew training research is the development of cost-effective, ground-based systems to provide realistic, mission-specific training environments for experienced NVD aircrew members. While there are many aspects to advance NVD simulation, two fundamentally different approaches to creating the visual scene can be used in addressing this problem. One approach involves presenting a visual scene which is capable of stimulating an accurate response in the NVGs. The second approach is to simulate the scene as it would be interpreted by the NVGs. Preliminary evaluation of the image fidelity will be made by experienced NVG users.

<u>Stimulating NVGs</u>. Our existing limited field of view dome simulator with a F-16A cockpit and the AVTS have been modified for use with our Initial NVD Training Course. The aviator flies the simulator with actual night vision goggles in place and operational. The head tracked area-of-interest (AOI) provides a 30 X 40 degree field of view with a monochromatic image. The scene illumination is reduces using neutral density filters. In lieu of the blend filter normally used to block the background projections in the AOI, a neutral density filter combination is used to darken the black field and overlay bright, low resolution, light faces on the AOI scene. This projection technique in conjunction with database and software modifications is effectively used to stimulate the NVGs.

Simulating NVGs. The second approach is to provide a visual image which simulates the response of the NVG. A recent innovative effort underway is to use a developmental 525-line helmet-mounted CRT display. This device provides an infinity focused 40 degree field of view. By integrating the helmet-mounted CRT system with the AVTS imagery, the sensor imagery of NVGs can potentially be more closely duplicated.

SUMMARY

As you can see, the Night Vision Device Program at Williams focuses on the development ground-based training techniques and facilities to enable aircrew member to obtain optimum performance with their visual devices under compromising conditions.